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RADIOSCIENCE LABORATORY

STANFORD ELECTRONICS LABORATORIES

STANFORD UNIVERSITY · STANFORD, CALIFORNIA

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ADAPTATION OF THE KIFT-FOOKS IONOSPHERIC RAY-TRACING TECHNIQUE TO A HIGH-SPEED DIGITAL COMPUTER

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Stanford University Stanford, California

ABSTRACT

This report describes a modified ray-tracing technique used in the synthesis of oblique-incidence, step-frequency ionograms. Ionograms of this type are obtained experimentally to aid in the real-time selection of frequencies for point-to-point communications and propagation studies. When it is desirable to identify the modes of propagation, computer-calculated ray tracings have proved quite valuable.

The Kift-Fooks ray-tracing technique was chosen because it is a rapid program capable of tracing rays when only a minimum of ionospheric data is available. One could utilize this technique in the analysis of propagation data either by synthesizing an oblique-incidence ionogram for direct comparison with experimentally observed results or by comparing plots of maximum usable frequency (predicted) with receiving-station log sheets. The details of the computer program are included with instructions that may be used as a guide by anyone familiar with computers and programming operations to perform his own calculations.

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TABLES

ILLUSTRATIONS

LIST OF SYMBOLS

d	distance to any point along the great-circle path
f	frequency
f_h	gyro frequency
f_o	critical frequency of a layer
f_oE	FOE = critical frequency of the E layer
f_oF1	FOF1 = critical frequency of the F1 layer
f_oF2	FOF2 = critical frequency of the F2 layer
f_oE_s	FOES = critical frequency of the ES layer
h	height
h_o	height at the bottom of a parabolic layer
h_r	height of reflection
h_m	height of the maximum electron density of a layer
h_mE	height of the maximum electron density of the E layer
h_mF1	height of the maximum electron density of the F1 layer
h_mF2	HT FOF2 = height of the maximum electron density of the F2 layer
i	angle between ray path and vertical at any point along the path
p'	time delay
x	ratio of the F2 4000 MUF to the f_oF2
D	distance ray propagates
DB	attenuation due to D-layer absorption
F2 4000 MUF	maximum usable frequency for 1-hop F2-layer propagation
LOF	lowest observed frequency
MOF	maximum observed frequency
M3000	ratio of the F2 3000 MUF to the f_oF2
N	number of ray passages through the D layer

R	radius of the earth
SSN	sunspot number
T	time in hours (universal time)
Y_m	semi thickness of a parabolic layer
$Y_m E$	semi thickness of the parabolic E layer
$Y_m F1$	semi thickness of the parabolic F1 layer
α	bearing of receiver from transmitter (degrees East of North)
β	take-off angle (above the horizon)
θ_o	longitude of transmitter
θ_1	longitude of point on path
θ_2	longitude of the sun
λ_o	latitude of transmitter
λ_1	latitude of point on path
λ_2	declination of sun
ϕ_o	φ_o = angle of incidence, measured from vertical, at the bottom of the ionosphere
ϕ_r	φ_r = angle of incidence, measured from vertical, at the real height of reflection
ϕ_D	φ_D = angle of incidence, measured from vertical, at the bottom of the D layer
χ	solar zenith angle
Δ	take-off angle (above the horizon)
ΔD	ground distance for a ray passing through a layer
$\Delta P'$	virtual distance along a ray passing through a layer

ACKNOWLEDGMENTS

The suggestions of Mr. F. Kift and Dr. G. Fooks played an important part in the beginning of this work and are gratefully acknowledged. Thanks are also due to the staff of the Radioscience Laboratory of Stanford University and to its Director, Professor O. G. Villard, Jr., for their assistance, guidance, and continued helpfulness.

Digital computations were partially financed under NSF-GP948, a grant which has materially contributed to the excellence of the Stanford Computation Center.

I. INTRODUCTION

In an effort to understand better the propagation characteristics associated with fixed-frequency transmissions over a long (8000-km), east-west path (i.e., Hawaii to Massachusetts), it was decided to instrument this path with a step-frequency (4-64-Mc) transmitter and a synchronized receiver. With the above equipment operating on a round-the-clock basis, it was hoped that records could be obtained that would permit deduction of the mode structure and apparent ray path of the propagating signals.

Examination of the records taken on this path, soon indicates that the usual simplifying assumptions (such as a uniform ionosphere over the entire path) are often not representative of what is happening. The path, 8000 km long, is just on the edge of the normally assumed "allowable" two-hop, F2-layer propagation. Records show that the 2F2 mode propagates for only short periods around noon and midnight, local time, at the midpoint of the path. At other times (especially sunrise and sunset), the progressive change across the path from a daytime ionosphere (with E, F1, and F2 layers) to a nighttime ionosphere (F2 layer only) produces a bewildering variety of propagation modes. Analysis soon becomes fairly complex. To assist in the understanding of the mode structure, it was felt that a ray-tracing program that simulated the experimental data would help.

Familiarity with the experimental technique and record form will help in understanding the type of information that would be desirable from computed ray tracings. The experimental data were obtained in the following way. The transmitter and receiver include electronically tuned and synchronized circuitry that ranges in frequency from 4 to 64 Mc in 160 steps-40 linearly spaced steps per octave band. Pulses, 50 μsec in duration, are transmitted over the Hawaii-

Massachusetts path, and the received pulses (differentially delayed in time as a result of the different modes of propagation) are recorded on film using the following technique. An oscilloscope is intensity modulated with the detected video output of the receiver. As the transmitter and receiver step in frequency over the operating range, the display is recorded on moving film, producing a record showing time delay as a function of frequency. This presentation is referred to as an oblique-incidence ionogram. An artist's sketch of this type of record is shown in Fig. 1.

The primary characteristics that one would hope to obtain from a ray-tracing analysis for comparison with the experimental results are summerized below:

1. The Maximum Observed Frequency (MOF) and the Lowest Observed Frequency (LOF) for each of the modes (e.g., mode 1,2,3,...).
2. The differential group time delay separating each of the modes at any given frequency (e.g., f_1).

In addition, it would be desirable to obtain a profile view of the propagation path showing the rays, their ground-reflection points and the apparent path of the rays through the ionosphere. An example of this is given in Fig. 2, showing the three modes of the ionogram of Fig. 1, at a fixed frequency f_1.

II. AVAILABLE RAY-TRACING TECHNIQUES

The problem in synthesizing an oblique-incidence ionogram by a ray-tracing approach is actually twofold:

1. Can the mode structure be duplicated by a ray-tracing approach if sufficient ionospheric data are available?
2. In the absence of this ionospheric data, could the CRPL ionospheric-propagation predictions, available three months in advance, be used in conjunction with the ray-tracing program to predict the mode structure likely to be observed?

With this problem in mind, it was decided first to find out how other researchers had solved this or similar problems. Inquiry into the available ray-tracing techniques necessitated visiting various establishments to find out the latest information; at that time, much of it was as yet unpublished. However, since then, a meeting has been held in Lindau, Germany, to discuss oblique-incidence soundings and ionospheric ray tracing.

Table 1* is a summary of ray-tracing techniques.

An alternate possibility, the use of an analog computer to solve the ray-tracing equations, has been utilized by Wong [Ref. 17]. The difficulty in using an analog computer is that the output, height vs range (as a function of frequency), gives the distribution of energy along the great circle but does not "home-in" on the receiver (a point at a fixed range).

* This information is based on material that appeared in the "Report of the Lindau Meeting on Oblique Sounding of the Ionosphere," May 6-10, 1963. Meeting held at: Institut Für Ionsopharen-Physik, Max-Planck-Institut Für Aeronomie, Lindau Über Northeim, Germany.

TABLE 1. RAY-TRACING TECHNIQUES

Class	Assumptions	Advantages
Equivalence Method	Plane earth; plane ionosphere; no magnetic field. [Ref. 1]	Extreme simplicity, enabling one to obtain an order-of-magnitude calculation of time delay and distance even when no ionogram is available; useful on short paths.
	Plane earth; plane ionosphere. [Ref. 2]	Allows determination of effects of earth's magnetic field.
Overlay Methods	Concentric layers with no magnetic field; empirically corrected, however, angle curves are based on Martyn's equivalence theorem. [Ref. 3]	Enables use of a slider in calculating apparent ray paths. Use of sliders in scaling the M3000 factor from vertical-incidence ionograms is important since these data are used by CRPL in their prediction techniques.
	Concentric layers. [Ref. 4]	Corrects for magnetic field in generating a slider for any given ionospheric profile; particularly useful in analyzing long-distance propagation paths with low angles of elevation.
Inverse slider	Same as that of slider used. [Ref. 5]	Inverse slider technique enabling quick identification of the modes on an oblique-incidence ionogram and the vertical incidence ionogram, at the path midpoint, to be determined.
Concentric ionosphere	Parabolic layers; no magnetic field. [Ref. 6]	Reference to the published ionograms provides a simple method of ray tracing in a parabolic layer.
	Synthesis of ionospheric profiles with line segments. [Refs. 7,8,9]	Profile may be accurately represented.

Class	Assumptions	Advantages
	Approximately constant magnetic field; can use any profile as above [Ref. 10]	A general expression is developed enabling direct calculation of the ray-path length using a simple ray treatment.
	Parabolic layers; no magnetic field; constant ratio for Ym/ho other layers, fixed foF1 = 1.4 foE; foE = 0 for $\chi \geq 70^{\circ}$; otherwise, foE = $g(\cos^4\chi)$ [Refs. 11,12]	By assuming concentric ionosphere for each hop but calculating each layer as it is first encountered, one can include first-order effects of a horizontal gradient in electron density; homing-in on the receiver is provided, allowing rapid calculation to identify modes of propagation and to predict MUF's and ray paths from the CRPL predictions.
Skewed ionosphere	Same as above [Ref. 13]	Inclusion of tilts by correction of ϕ_0 at entry into and exit from the layers may give a refinement to the method described above.
Isotonic contours	Hazelgrove equations [Ref. 14]	The ray path can be approached more realistically, thus providing more accurate ray paths in the regions of extreme tilts or gradients along the great circle.
Three dimensional	Tilting mirror reflector in the ionosphere; Martyn's equivalence theorem [Ref.15]	Gives a first-order approximation to super-modes and off-great-circle-path propagation. Nomograms are available for some heights and distances; others can be calculated and plotted by use of a 7090 computer.
	Hazelgrove equations [Ref. 16]	Most thorough analysis when ionospheric can be specified in great detail; has homing-in feature incorporated.

The "home-in" capability afforded by a digital-computer program is an attractive feature. Sorting by modes and range discrimination greatly simplifies the handling of the enormous amounts of data that are calculated by the computer. One is thus able to concentrate on the path in question, having already sorted out the rays that never reach the receiver.

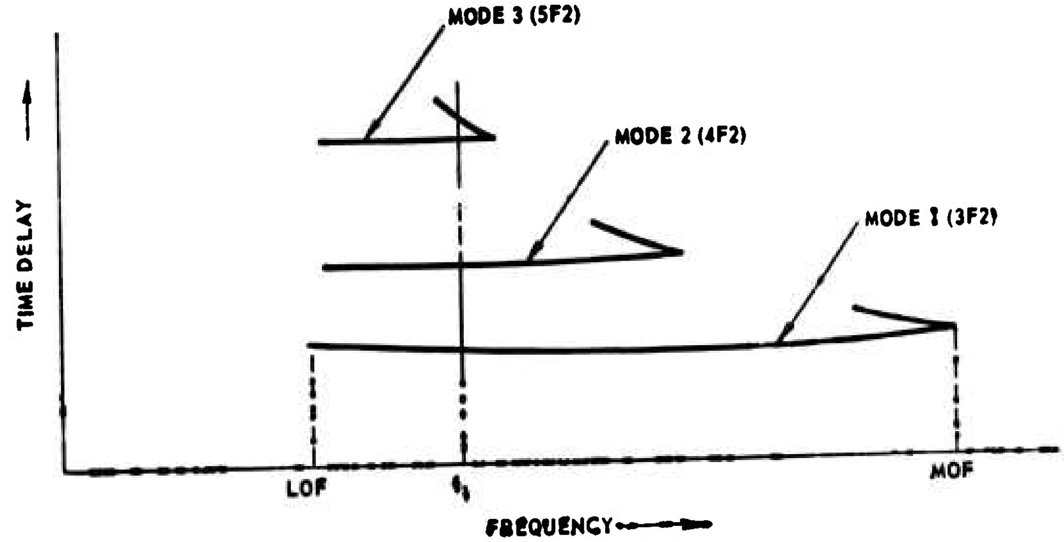


FIG. 1. THEORETICAL VERSION OF AN OBLIQUE-INCIDENCE, SWEEP-FREQUENCY IONOGRAM.

III. CHOICE OF THE KIFT-FOOKS TECHNIQUE

To synthesize an oblique-incidence ionogram (Fig. 1), it is necessary to consider only those rays that reach the receiver. Detailed knowledge of the ionosphere is not always available and, where predictions are concerned, a detailed ray-tracing approach is not justified. In fact, most of the time, only a bare minimum of data exists concerning the true electron-density profile along any given path. Even with electron-density distributions, assumptions as to the structure of the magnetic field, the off-great-circle profiles, as well as a choice of a magneto-ionic theory, need to be made prior to the use of a complete three-dimensional analysis [Ref. 16].

With these limitations, it was believed that a program which takes into account the gross changes in the ionosphere along a path at sunrise and sunset, by the inclusion of the daytime E and F1 layers and a specularly reflecting sporadic E layer, would suffice.

The major factors governing the choice of the Kift-Fooks technique were probably the rapidity with which the program could be run on a truly high-speed digital computer (either the IBM7090 or the IBM 7094) and the fact that predictions could be made, using the CRPL ionospheric propagation-predictions in their present card format [Ref. 18], on a highly automated basis.

Thus, it was decided to use the ray-tracing technique suggested by Kift [Ref. 11] and programmed for use on the Pegasus computer by Fooks [Ref. 12]. The advantages of this program are that it assumes a set of parabolic layers for the ionospheric profile and then calculates the ray path in (or through) a parabolic layer by the Appleton-Beynon [Ref. 6] equations.

Some of the inaccuracies of this technique are pointed out by Kift at the end of his article, with reference to the work of Vickers [Ref. 19]. A report that compares the Kift-Fooks technique with a more accurate technique, developed by Croft [Ref. 20], is soon to be published as another report in this series.

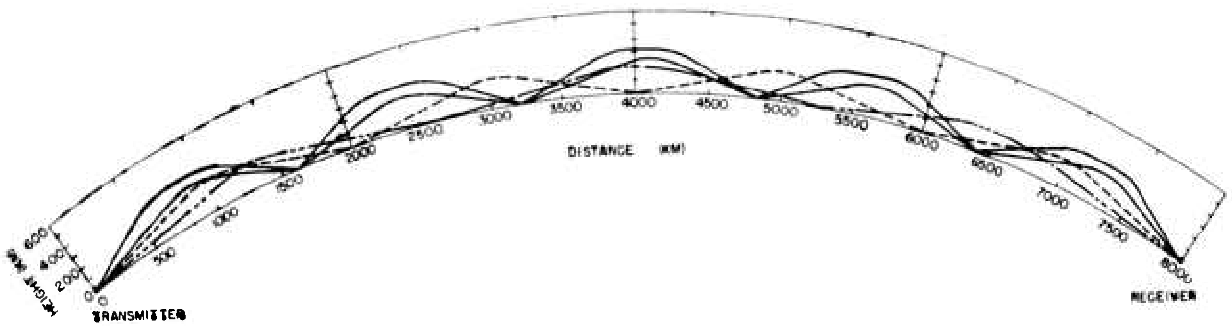


FIG. 2. CROSS SECTION OF IONOSPHERIC RAY PATHS.

IV. HOW TO UTILIZE THE KIFT-FOOKS TECHNIQUE

Before attempting to utilize the Kift-Fooks technique in the analysis of point-to-point propagation characteristics, one should know what data are available in the print-out of the program and how to use these data.

Table 2 lists the ionospheric-profile parameters along the great-circle path (from the transmitter to the receiver) in 100-km intervals. The values given are the critical frequencies of the E, F1, and F2 layers, and the height at which the maximum of the F2 layer occurs is given for the points mentioned above. Details of the exact computer output format (Tables 2,3,4) are given on pp. 11, 12, and 13.

Each ray-tracing group is identified by the transmitter latitude and longitude, the bearing to the receiver, and the time, month, and year for which the ionosphere was compiled.

An example of the present data format is given in Table 3. The description of each mode includes: names of successive reflecting layers, frequency, take-off angle, group time delay, and attenuation. The terminology used in this format is different from that recommended for use in oblique-incidence work (Appendix A). However, since this report is intended to explain the ray-tracing program in its present form, inclusion of the recommended nomenclature would have necessitated further delays.

The modes are listed in terms of increasing frequency and take-off angle (for any one frequency).

In addition, an option available to the program prints out the ground range and height of the ray for points of entry or exit of a layer and the ground-reflection points (Table 4). Thus a ray plot similar to that shown in Figure 2 could be plotted from the data of Table 4.

With knowledge of the output format in hand, one can now proceed with the discussion of how these data can be

used in the synthesis of an oblique-incidence ionogram (Fig. 1). Refferring to Table 3 and establishing the same set of coordinates as that achieved experimentally, one would then plot and join together points having the same mode description (i.e., .F1 .E .E .E .E). This plot could then be compared directly with the experimentally achieved data. Please note, however, that there will be an omission of the high-angle rays because of the method used in programming the computer for mode calculation and retention.

When the take-off angle and the attenuation associated with a given mode are taken into account, a first-order approximation can be made to eliminate many of the predicted modes that experience tells us just wouldn't get through.

Using vertical-incidence soundings made along or near the great circle, as a first-order correction to the CRPL prediction, enables greater accuracy to be achieved, particularly if patches of sporadic E are present which were not taken into account in the predictions. A subsequent report will be issued outlining the procedure used in this case (i.e., an after-the-fact analysis).

However, it is most important to emphasize once again the main advantage of the Kift-Fooks technique as a predictor of propagation conditions. Certainly, when detailed information regarding the ionospheric profile is available, it would make sense to utilize one of the more detailed ray-tracing programs currently available [Refs. 9,14,16,20].

By directly converting the CRPL ionospheric propagation predictions into values of f_oF2 and M3000 (the ratio of the 3000 Km MUF to the f_oF2) and subsequently using the assumption of Kift and Fooks [Refs. 11 and 12, respectively], the computer can calculate the values of height of the maximum of the F2 layer and trace all subsequent rays that reach the receiver.

Thus we have a highly automated prediction program, the details of which are specified in the following sections.

TABLE 2. IONOSPHERIC-PROFILE PARAMETERS

IONOSPHERIC PROFILE FOR 6 OCTOBER 1962 1737.36 GMT PANJA/BEDFORD PATH

FOE	FOF1	FOF2	HT FOF2	RANGE
3.3	4.6	7.5	205.55	0.
0.	0.	7.5	207.13	100.00
0.	0.	7.5	208.93	200.00
0.	0.	7.5	210.97	300.00
0.	0.	7.5	213.23	400.00
0.	0.	7.6	215.73	500.00
0.	0.	7.6	218.45	600.00
0.	0.	7.6	221.39	700.00
0.	0.	7.6	224.57	800.00
0.	0.	7.6	229.28	900.00
2.5	3.6	7.6	233.33	1000.00
2.6	3.6	7.6	235.64	1100.00
2.6	3.6	7.6	239.19	1200.00
2.6	3.7	7.6	241.01	1300.00
2.6	3.7	7.6	242.07	1400.00
2.6	3.7	7.6	242.39	1500.00
2.7	3.7	7.6	241.97	1600.00
2.7	3.8	7.6	242.79	1700.00
2.7	3.8	7.6	243.30	1800.00
2.7	3.8	7.6	243.33	1900.00
2.7	3.8	7.6	242.87	2000.00
2.8	3.9	7.6	241.93	2100.00
2.8	3.9	7.6	240.50	2200.00
2.8	3.9	7.6	238.58	2300.00
2.8	3.9	7.6	236.19	2400.00
2.8	3.9	7.6	235.12	2500.00
2.8	4.0	7.6	234.25	2600.00
2.8	4.0	7.6	233.34	2700.00
2.9	4.0	7.6	232.37	2800.00
2.9	4.0	7.5	231.35	2900.00
2.9	4.0	7.5	230.27	3000.00
2.9	4.1	7.5	229.14	3100.00
2.9	4.1	7.5	227.96	3200.00
2.9	4.1	7.5	224.86	3300.00
2.9	4.1	7.5	222.96	3400.00
2.9	4.1	7.5	219.99	3500.00
3.0	4.1	7.5	216.67	3600.00
3.0	4.2	7.5	[illegible]	3700.00
3.0	4.2	7.5	21[illegible].27	3800.00
3.0	4.2	7.5	219.20	3900.00
3.0	4.2	7.5	220.37	4000.00
3.0	4.2	7.5	222.05	4100.00
3.0	4.2	7.5	222.96	4200.00
3.0	4.2	7.5	223.90	4300.00
3.0	4.2	7.5	224.35	4400.00
3.0	4.3	7.5	225.45	4500.00
3.0	4.3	7.5	226.35	4600.00
3.1	4.3	7.6	227.98	4700.00
3.1	4.3	7.6	228.93	4800.00
3.1	4.3	7.6	230.21	4900.00
3.1	4.3	7.7	232.97	5000.00
3.1	4.3	7.7	235.12	5100.00
3.1	4.3	7.7	237.25	5200.00
3.1	4.3	7.7	239.36	5300.00
3.1	4.3	7.7	241.45	5400.00
3.1	4.3	7.7	243.52	5500.00
3.1	4.4	7.7	245.58	5600.00
3.1	4.4	7.7	247.87	5700.00
3.1	4.4	7.7	250.19	5800.00
3.1	4.4	7.7	252.39	5900.00
3.1	4.4	7.7	254.49	6000.00
3.1	4.4	7.8	256.48	6100.00
3.1	4.4	7.8	258.36	6200.00
3.1	4.4	7.8	260.13	6300.00
3.1	4.4	7.8	261.79	6400.00
3.1	4.4	7.8	264.08	6500.00
3.1	4.4	7.8	265.26	6600.00
3.1	4.4	7.8	267.80	6700.00
3.2	4.4	7.9	268.70	6800.00
3.2	4.4	7.9	269.96	6900.00
3.2	4.4	7.9	268.57	7000.00
3.2	4.4	7.9	267.55	7100.00
3.2	4.4	7.9	265.89	7200.00
3.2	4.4	7.9	263.96	7300.00
3.2	4.4	8.0	262.29	7400.00
3.2	4.4	8.0	260.78	7500.00
3.2	4.4	8.0	259.41	7600.00
3.2	4.4	8.0	258.20	7700.00
3.2	4.4	8.0	257.15	7800.00
3.2	4.4	8.1	256.25	7900.00
3.2	4.4	8.1	255.50	8000.00
3.2	4.4	8.1	259.50	8100.00

TABLE 3. OBLIQUE-IONOGRAM OUTPUT DATA

6 OCTOBER 1962 1737.36 GMT PAHOA/BEDFORD PATH

PATH LENGTH 8045.35 KM TX LAT 19.50 DEG TX LONG -154.95 DEG [illegible] BEARING [illegible]

MODE										FREQ	BETA	[illegible]	[illegible]	D[illegible]	[illegible]
.E	.E	.E	.E							4.00	1.18	8039.09	[illegible].10	[illegible]	649.5[illegible]
.F2	.E	.E	.F	.E	.E	.E	.E	.E	.E	4.00	13.[illegible]9	8041.41	27.96	[illegible].94	[illegible].86
.E	.E	.E	.E							5.00	1.22	8037.90	27.09	[illegible]7.49	4[illegible].28
.E	.E	.E	.F							6.00	[illegible].28	8036.66	27.09	-8.69	[illegible]90.56
.E	.E	.E	.E							7.00	1.35	8035.48	27.09	[illegible]9.8[illegible]	213.86
.F2	.E	.E	.E	.E	.E	.E	.E	.E		7.00	12.50	8026.50	27.84	[illegible]18.85	275.9[illegible]
.F	.E	.E	.F							8.00	1.44	6034.5[illegible]	2[illegible].09	[illegible]10.78	163.9[illegible]
.E	.E	.E	.E							9.00	1.54	8034.34	27.10	-11.01	129.54
.E	.E	.E	.F							10.00	1.68	8035.43	27.12	[illegible]3.92	104.39
.F2	.F2	.F2	.F2	.F2	.F2	.F2				10.00	23.19	8015.76	30.17	-29.59	86.07
.E	.E	.E	.E							11.00	1.85	8039.26	27.16	-6.09	88.40
.F2	.F1	.F1	.F1	.F1						11.00	13.20	7989.22	28.10	-56.13	6[illegible].34
.F2	.F2	.F2	.F2	.F2	.F2	.F2				11.00	21.70	6024.18	29.87	-21.17	[illegible]7.77
.F2	.F2	.F2	.F2	.F2	.F2	.F2	.F2			11.00	24.17	8041.84	30.53	-3.51	6[illegible].41
.F1	.E	.E	.F	.E						12.00	7.01	6043.03	27.43	-2.32	71.98
.F2	.F2	.F2	.F2	.F2	.F2					12.00	18.43	8021.89	29.2[illegible]	-23.46	47.56
.F2	.F2	.F2	.F2	.F2	.F2	.F2				12.00	20.90	8040.18	29.80	-5.17	5[illegible].16
.F2	.F2	.F2	.F2	.F2	.F2	.F2	.F2			12.00	23.91	8042.93	30.44	-2.43	51.30
.F2	.F2	.F2	.F2	.F2						13.00	15.03	8042.09	28.83	-3.26	39.52
.F2	.F2	.F2	.F2	.F2	.F2					13.00	17.66	8031.37	29.15	-13.39	4[illegible].36
.F2	.F2	.F2	.F2	.F2	.F2	.F2				13.00	20.65	8042.70	29.77	-2.65	43.22
.F2	.F2	.F2	.F2	.F2	.F2	.F2	.F2			13.00	24.35	8037.02	30.59	-8.33	44.13
.F2	.F2	.F2	.F2	.F2						14.00	14.17	8038.79	28.68	-6.36	35.63
.F2	.F2	.F2	.F2	.F2	.F2					14.00	17.32	8037.78	29.13	-7.37	36.79
.F2	.F2	.F2	.F2	.F2	.F2	.F2				14.00	20.86	8048.51	29.87	3.16	37.01
.F2	.F2	.F2	.F2							15.00	10.72	8018.50	28.16	-26.85	29.88
.F2	.F2	.F2	.F2	.F2						15.00	13.72	8033.63	28.57	-11.72	31.79
.F2	.F2	.F2	.F2	.F2	.F2					15.00	17.35	8042.26	29.18	-3.09	32.05
.F2	.F2	.F2	.F2	.F2	.F2	.F2				15.00	22.10	8045.07	30.17	-0.28	30.80
.F2	.F2	.F2	.F2							16.00	10.03	8044.89	28.26	-0.46	27.36
.F2	.F2	.F2	.F2	.F2						16.00	13.52	8036.26	28.36	-9.09	24.27
.F2	.F2	.F2	.F2	.F2	.F2					16.00	17.62	6047.48	29.33	2.13	27.63
.F2	.F2	.F2								17.00	6.29	8026.07	27.85	-19.33	22.57
.F2	.F2	.F2	.F2							17.00	9.66	8040.63	28.17	-4.72	24.79
.F2	.F2	.F2	.F2	.F2						17.00	13.56	6043.77	28.63	-1.38	25.01
.F2	.F2									18.00	0.26	8055.64	27.76	10.29	16.60
.F2	.F2	.F2								18.00	5.64	8046.42	27.92	1.07	2[illegible].88
.F2	.F2	.F2	.F2							18.00	9.49	8042.59	28.17	-2.76	22.35
.F2	.F2	.F2	.F2	.F2						18.00	13.91	8040.59	28.69	-4.76	21.95
.F2	.F2	.F2								19.00	5.28	8040.53	27.86	-4.82	19.12
.F2	.F2	.F2	.F2							19.00	9.51	8042.76	28.18	-2.59	20.05
.F2	.F2	.F2	.F2	.F2						19.00	15.25	8033.20	28.90	-12.15	18.64
.F2	.F2	.F2								20.00	5.08	8042.24	27.84	-3.11	17.45
.F2	.F2	.F2	.F2							20.00	9.73	8042.64	28.22	-2.71	17.89
.F2	.F2	.F2								21.00	5.02	8044.62	27.86	-0.73	15.90
.F2	.F2	.F2	.F2							21.00	10.22	8045.00	28.32	-0.35	15.80
.F2	.F2	.F2								22.00	5.09	8042.56	27.86	-2.79	14.45
.F2	.F2	.F2								23.00	5.29	6037.81	27.86	-7.54	13.09
.F2	.F2	.F2								24.00	5.68	8040.43	27.93	-4.92	11.79
.F2	.F2	.F2								25.00	6.71	8016.11	27.91	-29.24	10.27

TABLE 4. RAY-PATH OUTPUT DATA

6 OCTOBER 1962 1737.36 GMT PAHOA/BEDFORD PATH

PATH LENGTH 8045.35 KM TX LAT 19.50 DEG TX LONG -154.95 DEG RX BEARING 50.26 DEG

MODE .F1 .E .E .E .E

12.000 MC 7.005 DEGREES

HEIGHT	RANGE
140.00	753.85
187.17	1095.09
100.00	1920.36
0.	2512.50
112.74	3220.64
0.	3944.77
110.83	4635.49
0.	5326.21
110.00	6006.97
0.	6687.74
109.73	7365.38
0.	8043.03

6 OCTOBER 1962 1737.36 GMT PAHOA/BEDFORD PATH TX LONG -154.95 DEG RX BEARING 50.26 DEG

PATH LENGTH 8045.35 KM TX LAT 19.50 DEG

MODE .F2 .F2 .F2 .F2 .F2 .F2

12.000 MC 18.426 DEGREES

HEIGHT	RANGE
140.00	377.77
169.34	480.10
150.00	558.15
100.00	682.74
0.	960.20
140.00	1353.26
149.43	1599.69
150.00	1822.38
100.00	1966.47
0.	2261.93
140.00	2638.60
179.96	2893.49
150.00	3124.21
100.00	3269.73
0.	3547.19
140.00	3947.12
174.68	4222.29
150.00	4473.56
100.00	4621.89
0.	4899.35
140.00	5301.74
193.95	5655.36
150.00	5987.47
100.00	6137.81
0.	6415.27
140.00	6819.16
204.79	7218.02
150.00	7593.56
100.00	7744.43
0.	8021.89

6 OCTOBER 1962 1737.36 GMT PAHOA/BEDFORD PATH TX LONG -154.95 DEG RX BEARING 50.26 DEG

PATH LENGTH 8045.35 KM TX LAT 19.50 DEG

MODE .F2 .F2 .F2 .F2 .F2 .F2 .F2

12.000 MC 20.904 DEGREES

HEIGHT	RANGE
140.00	335.66
170.63	437.73
150.00	517.86
100.00	630.00
0.	875.45
140.00	1221.78
192.09	1437.13
150.00	1630.90
100.00	1755.06
0.	2000.51
140.00	2349.05
185.51	2566.21
150.00	2761.59
100.00	2887.79
0.	3133.23
140.00	3483.69
172.86	3687.70
150.00	3869.37
100.00	3997.23
0.	4242.68
140.00	4594.63
182.54	4833.54
150.00	5050.80
100.00	5179.98
0.	5425.43
140.00	5778.50
203.42	6074.58
150.00	6349.59
100.00	6479.62
0.	6725.06
140.00	7078.75
205.60	7382.56
150.00	7664.54
100.00	7794.74
0.	8040.18

6 OCTOBER 1962 1737.36 GMT PAHOA/BEDFORD PATH

PATH LENGTH 8045.35 KM TX LAT 19.50 DEG TX LONG -154.95 DEG RX BEARING 50.26 DEG

MODE .F2 .F2 .F2 .F2 .F2 .F2 .F2 .F2

12.000 MC 23.913 DEGREES

HEIGHT	RANGE
140.00	293.76
173.20	398.68
150.00	484.11
100.00	583.39
0.	797.36
140.00	1091.12
195.22	1284.51
150.00	1458.78
100.00	1566.10
0.	1780.07
140.00	2082.37
192.95	2280.54
150.00	2459.57
100.00	2568.11
0.	2782.07
140.00	3085.53
182.28	3270.43
150.00	3435.88
100.00	3545.43
0.	3759.39
140.00	4063.79
181.43	4253.98
150.00	4424.74
100.00	4535.11
0.	4749.08
140.00	5054.20
193.38	5272.70
150.00	5472.17
100.00	5583.17
0.	5797.13
140.00	6102.78
212.32	6361.74
150.00	6601.58
100.00	6712.95
0.	6926.92
140.00	7232.82
208.56	7484.94
150.00	7717.57
100.00	7828.99
0.	8042.95

6 OCTOBER 1962 1737.36 GMT PAHOA/BEDFORD PATH

PATH LENGTH 8045.35 KM TX LAT 19.50 DEG TX LONG -154.95 DEG RX BEARING 50.26 DEG

MODE .F2 .F2 .F2

13.000 MC 6.285 DEGREES

HEIGHT	RANGE
140.00	795.34
188.09	1164.93
150.00	1494.02
100.00	1755.57
0.	2376.09
140.00	3229.29
169.62	3636.69
150.00	4001.77
100.00	4285.17
0.	4905.69
140.00	5777.34
208.33	6457.01
150.00	7109.07
100.00	7405.51
0.	8026.02

6 OCTOBER 1962 1737.36 GMT PAHOA/BEDFORD PATH

PATH LENGTH 8045.35 KM TX LAT 19.50 DEG TX LONG -154.95 DEG RX BEARING 50.26 DEG

MODE .F2 .F2 .F2 .F2

17.000 MC 9.659 DEGREES

HEIGHT	RANGE
160.00	625.52
182.75	825.41
150.00	989.93
100.00	1199.92
0.	1674.83
140.00	2328.72
185.03	2663.34
150.00	2962.70
100.00	3181.45
0.	3656.36
140.00	4310.01
181.36	4680.38
150.00	5007.72
100.00	5232.91
0.	5707.82
140.00	6374.27
213.76	6873.11
150.00	7337.97
100.00	7565.72
0.	8040.63

6 OCTOBER 1962 1737.36 GMT PAHOA/BEDFORD PATH

PATH LENGTH 8045.35 KM TX LAT 19.50 DEG TX LONG -154.95 DEG RX BEARING 50.26 DEG

MODE .F2 .F2 .F2 .F2 .F2

17.000 MC 13.565 DEGREES

WEIGHT	RANGE
140.00	490.10
181.89	678.10
150.00	836.21
100.00	1003.83
0.	1368.75
140.00	1873.05
197.43	2178.60
150.00	2455.21
100.00	2626.44
0.	2991.36
140.00	3498.91
178.86	3763.34
150.00	3997.72
100.00	4171.58
0.	4536.50
140.00	5046.28
198.22	5380.85
150.00	5686.20
100.00	5861.96
0.	6226.78
140.00	6737.86
217.70	7135.07
150.00	7502.65
100.00	7678.85
0.	8043.77

V. THE KIFT-FOOKS RAY TRACING PROGRAM

The ionospheric ray-tracing program described here is essentially the same as that described by G. F. Fooks in his report [Ref. 12]. The same equations are used and the same basic procedure is followed; however, certain modifications and additions to the program have been made to allow the calculations of reflection heights from the ionospheric layers, and to allow the calculation of an approximate value for ray attenuation due to D-layer absorption along the path.

A. PHYSICAL ASSUMPTIONS

The program uses a curved-earth, curved-ionosphere geometry, and the ionosphere is assumed to consist of a number of curved layers, each with a parabolic electron-density distribution. The ionospheric layers considered are E, F_1 and F_2. A sporadic E layer (E_s) may also be included in the calculations; however, when it is, it is treated not as a parabolic layer, but rather as a thin, specularly reflecting sheet. The earth's magnetic field and layer tilts are ignored.

Figure 3 illustrates the geometry of the ionospheric layer structure.

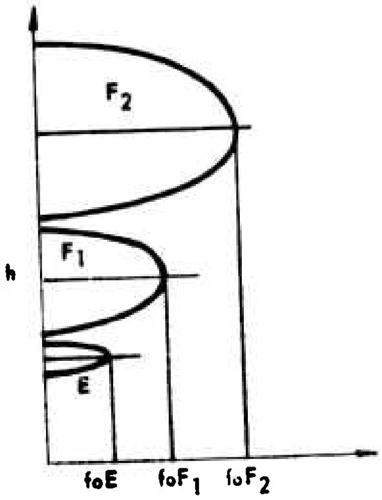


FIG. 3. IONOSPHERIC-LAYER STRUCTURE (PARABOLIC).

B. GENERATION OF THE IONOSPHERE

Figure 4 illustrates the geometric parameters for an arbitrary parabolic layer.

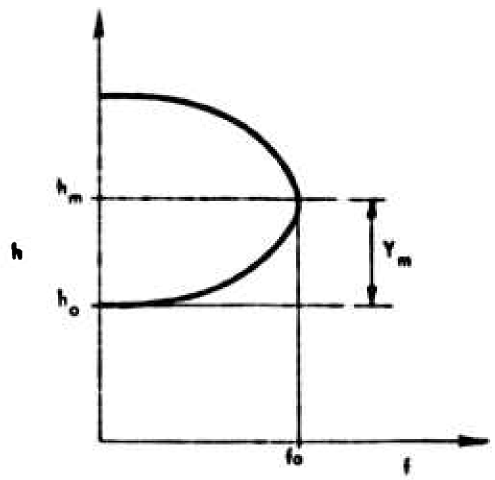


FIG. 4. GEOMETRIC PARAMETERS FOR AN ARBITRARY PARABOLIC LAYER.

Since the behavior of the E and F_1 layers is well understood, these layers are generated by several analytic expressions, which take into consideration the sunspot number and the solar zenith angle.

For the E layer we have:

$$\left.\begin{aligned} f_oE &= 3.4\,(1.0 + 0.0097 \cdot SSN)^{0.25} \cdot \cos^{0.33}\chi & \chi &\le 70^\circ \\ f_oE &= 0.0 & \chi &\le 70^\circ \\ h_mE &= 120.0 \text{ km} & & \\ y_mE &= 20.0 \text{ km}, & & \end{aligned}\right\} \quad (1)$$

where:

f_o = critical frequency for the layer in megacycles (vertical incidence)

SSN = sunspot number

χ = solar zenith angle.

For the F_1 layer:

$$\left.\begin{aligned} f_oF1 &= 1.4(f_oE) \\ h_mF_1 &= 210.0 \text{ km} \\ y_mF_1 &= 60.0 \text{ km} \end{aligned}\right\} \qquad (2)$$

For the F_2 layer, values of f_oF_2 and h_mF_2 are supplied to the program either as predicted values or observed values at arbitrary points along the path, and the program contructs a parabolic F_2 layer under the assumption:

$$y_mF_2 = 0.4\ h_oF_2, \qquad (3)$$

where $y_m = h_m - h_o$

Values of f_oE_s, if they are different from zero, are supplied to the program in terms of their position on the path. The height of the E_s layer is assumed constant at 100.0 km.

An equation for cos χ using the path geometry is presented in Appendix B.

In Appendix C a method is given for obtaining values of h_mF2 using predicted values of f_oF2 and F2 4000 MUF. These are the two parameters obtained from the CRPL ionospheric predictions.

C. EQUATIONS FOR RAY-PATH CALCULATIONS

Below the ionosphere and between ionospheric layers the ray is assumed to travel in a straight line.

The E_s layer either specularly reflects the ray or allows it to pass undeviated. For the parabolic layers the following equations apply:

$$\Delta P' = \frac{2f}{f_o} y_m \cdot \text{argtanh} \left(\frac{f}{f_o} \cos i\right) \qquad (4)$$

if the ray is reflected by the layer, and

$$\Delta P' = \frac{2f}{f_o} y_m \ \text{argcoth} \left(\frac{f}{f_o} \cos i\right) \qquad (5)$$

if the layer transmits the ray, but causes bending, where:

$\Delta P'$ = virtual path in the layer

f = wave frequency

f_o = layer critical frequency

i = angle between the ray, extrapolated along a straight line to the level of maximum electron density, and the vertical at that level (as illustrated in Fig. 5).

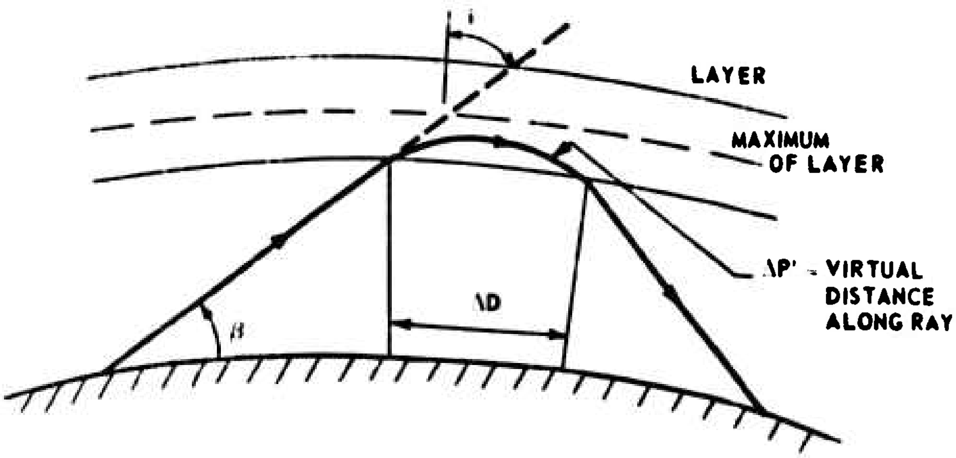


FIG. 5. OBLIQUE-INCIDENCE RAY-PATH GEOMETRY.

For transmission through a layer or for reflection from the bottom of a layer,

$$\Delta D = \frac{R}{R + h_m} \sin i \, \Delta P'. \qquad (6)$$

If the ray is reflected from the top of a layer,

$$\Delta D = \frac{R}{R - h_m} \sin i \, \Delta P', \qquad (7)$$

where ΔD is the range along the path covered while the ray is in the layer, and R is the earth's radius.

In the course of the ray tracing, as the ray enters a layer, there are three possible consequences:

1. The ray is reflected from the layer.
2. The ray is transmitted through the layer and deviated.
3. The ray is transmitted through the layer undeviated (straight-line transmission).

Let

$$K = (f/f_o) \cdot \cos i.$$

Then if

$$\left.\begin{array}{ll} K < 1 & \text{the ray is reflected} \\ K = 1 \quad P' = \infty , & \text{the next ray is taken} \\ 1 < K < 2 & \text{the ray is transmitted and deviated} \\ K \geq 2 & \text{the ray is transmitted and undeviated} \end{array}\right\} \quad (8)$$

The equations used for undeviated transmission through a layer, between layers, and from the ground to the bottom of the ionosphere are:

$$\sin i_2 = \frac{(R + h_1) \sin i_1}{(R + h_2)} \qquad (9)$$

$$\Delta P' = \frac{(R + h_2) \sin (i_1 - i_2)}{\sin i_1} \qquad (10)$$

$$\Delta D = R(i_1 - i_2) \qquad (11)$$

for straight-line transmission between two points at heights h_1 and h_2 with associated vertical angles i_1, and i_2.

During the course of the ray-tracing procedure, two layers may happen to overlap (most likely the F1 and F2 layers). When this occurs, the ray is extrapolated back along a straight-line path, tangential to its direction when it emerges from the first layer, to its point of entry to the second layer, (Fig. 6).

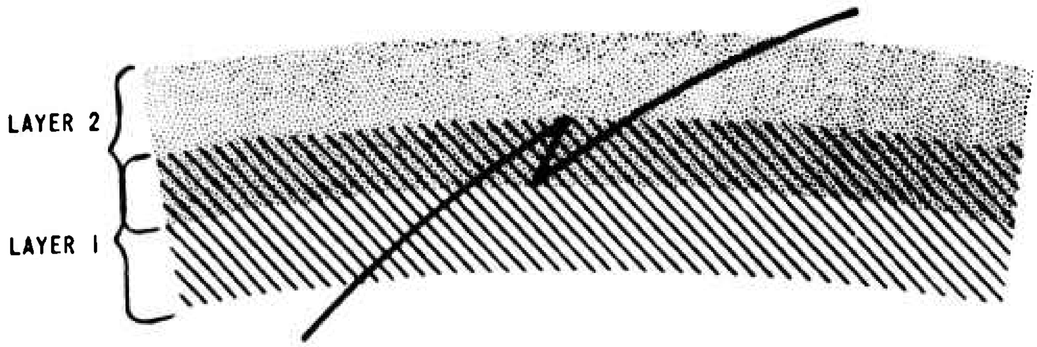


FIG. 6. OVERLAPPING-LAYER PROCEDURE

VI. STANFORD VERSION OF KIFT-FOOKS RAY-TRACING PROGRAM

A. BASIC COMPUTATIONAL PROCEDURE

Figure 7 is a logical flow diagram of the computational procedure; it is not intended as a detailed flow chart of the program, but merely as a gross logical description of the computational process.

The input data to the program are the path length between the receiver and the transmitter, the coordinates of the transmitter, the true bearing of the receiver from the transmitter, sunspot number, sun declination, apparent solar time at Greenwich; F_2-layer data in the form of either f_oF_2 and h_mF_2 or f_oF_2 and F_2 4000 MUF: E_s data, if any, plus a range of frequencies and a range of take-off angles to be investigated for the given ionosphere, and a set of frequencies for which ray-reflection-height information is desired. F_2 and E_s data are described in terms of their range along the path from the transmitter.

Once the data for the path have been read by the program, a table of ionospheric data is produced for use by the program. Equations (1) and (2) are evaluated at 100-km intervals along the path. A second-degree polynomial is fitted to successive triplets of f_oF_2 and h_mF_2 data points and these polynomials are evaluated at 100-km intervals along the path. Tables of E_s, if required, are compiled at 10-km intervals within each E_s patch considered. When, during ray tracing, values within the ionospheric tables are required between the calculated 100-km (10-km for E_s) points, linear interpolation is used.

After the generation of the ionospheric tables, the values of the critical frequency, f_o and height vs range for each layer are printed out (Table 2) and the actual ray-tracing process begins.

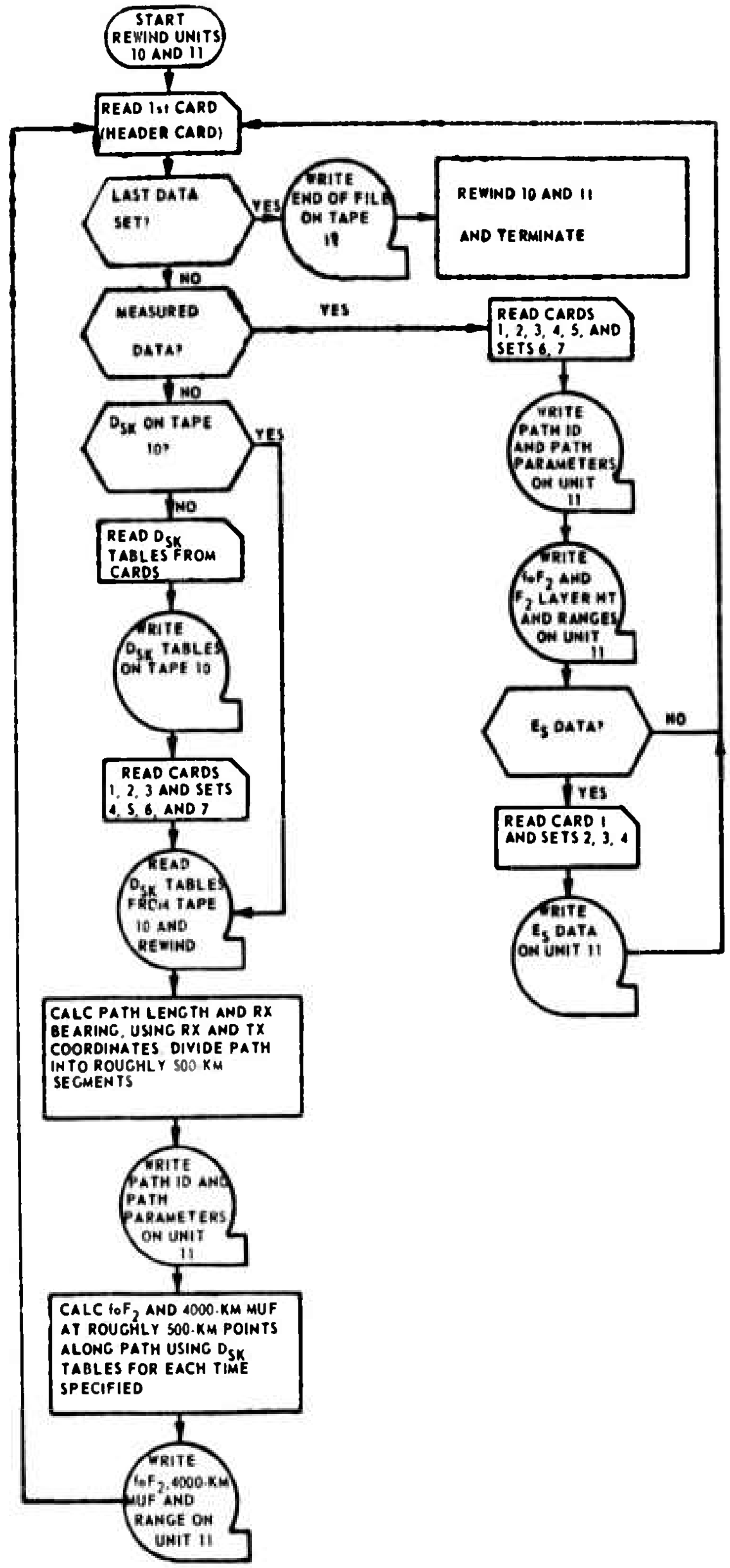


FIG. 7A DATA PROGRAM OF RAY-TRACE PROGRAM.

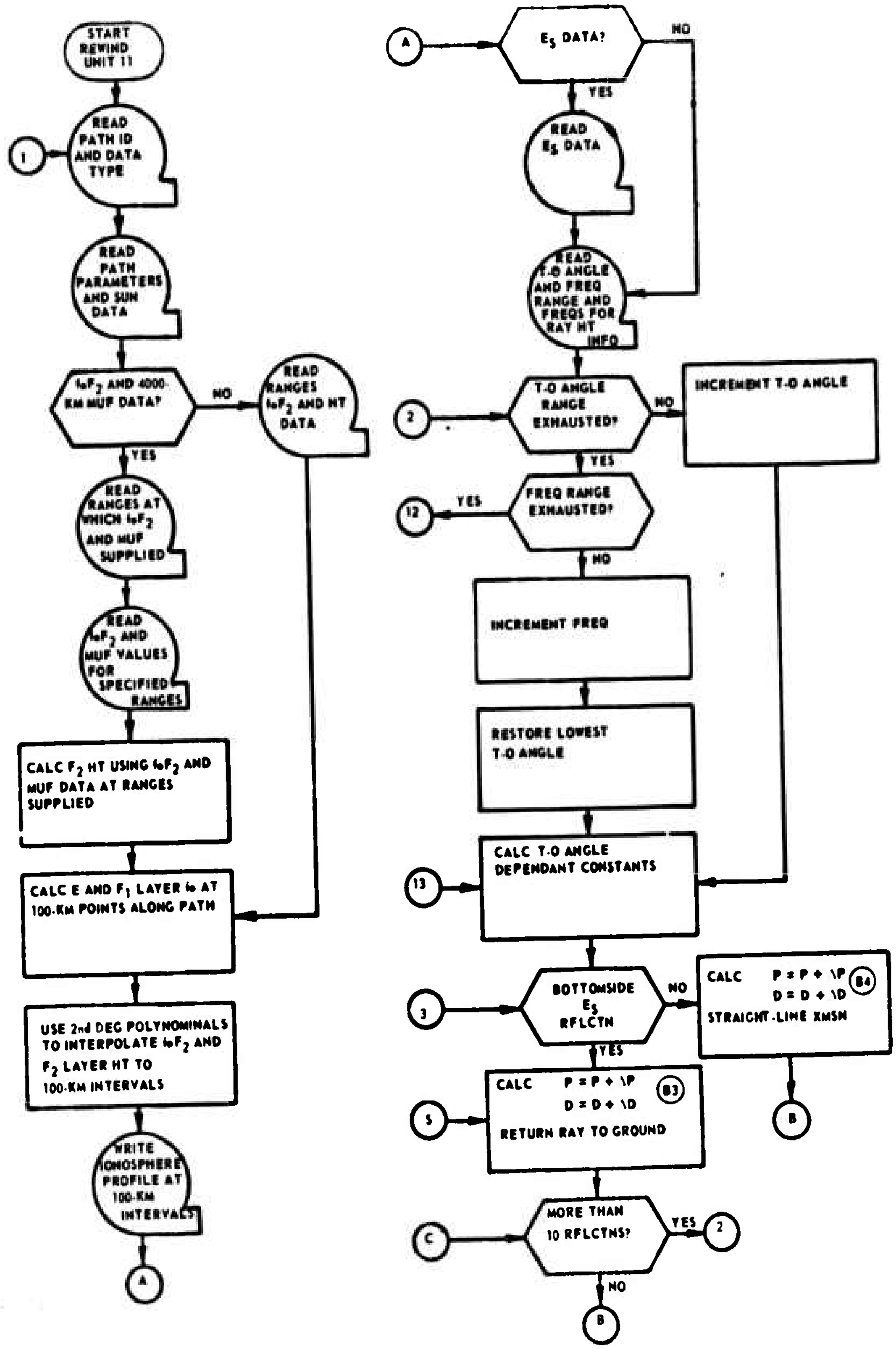
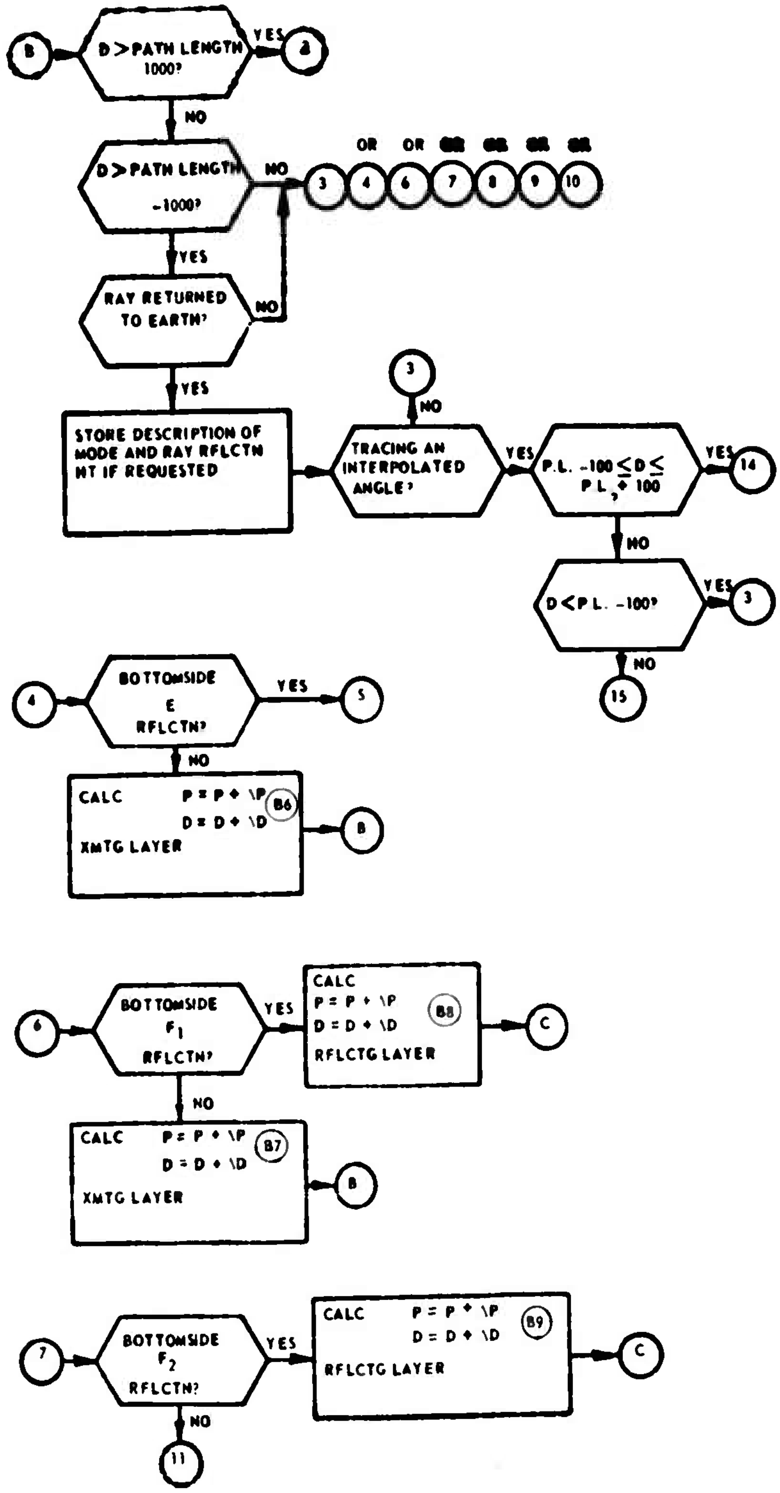
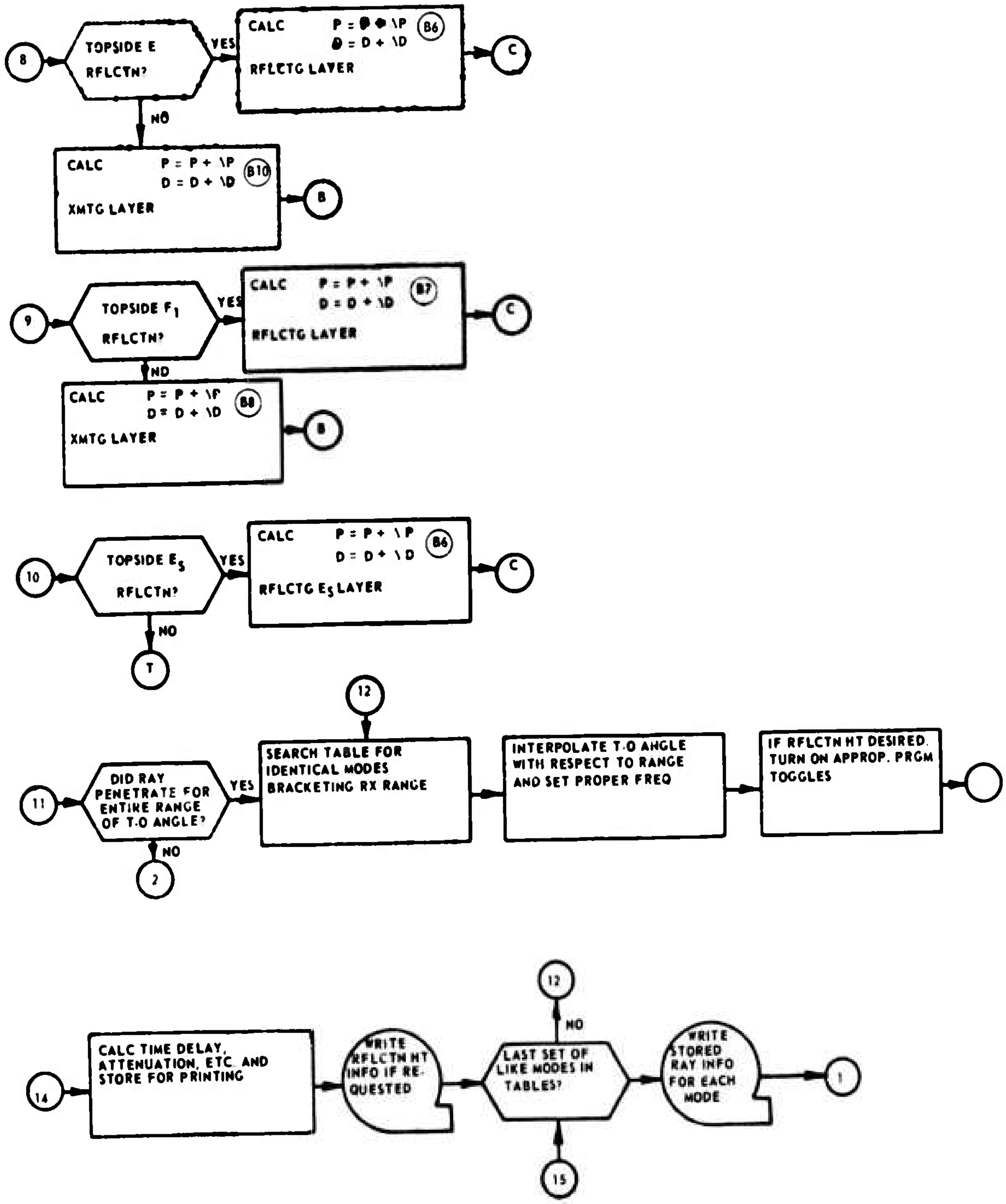


FIG. 7B FLOW DIAGRAM OF RAY-TRACE PROGRAM.



B
D > PATH LENGTH 1000?
YES
a
NO
D > PATH LENGTH -1000?
NO
OR OR
3 4 6 7 8 9 10
YES
RAY RETURNED TO EARTH?
NO
YES
STORE DESCRIPTION OF MODE AND RAY RFLCTN HT IF REQUESTED
3
NO
TRACING AN INTERPOLATED ANGLE?
YES
P.L. -100 ≤ D ≤ P.L. + 100
YES
14
NO
D < P.L. -100?
YES
3
NO
15
4
BOTTOMSIDE E RFLCTN?
YES
5
NO
CALC
P = P + \P
D = D + \D
B6
XMTG LAYER
B
6
BOTTOMSIDE F1 RFLCTN?
YES
CALC
P = P + \P
D = D + \D
B8
RFLCTG LAYER
C
NO
CALC
P = P + \P
D = D + \D
B7
XMTG LAYER
B
7
BOTTOMSIDE F2 RFLCTN?
YES
CALC
P = P + \P
D = D + \D
B9
RFLCTG LAYER
C
NO
11


8
TOPSIDE E RFLCTN?
YES
CALC P = P + \P D = D + \D
B6
RFLCTG LAYER
C
NO
CALC P = P + \P D = D + \D
B10
XMTG LAYER
B
9
TOPSIDE F1 RFLCTN?
YES
CALC P = P + \P D = D + \D
B7
RFLCTG LAYER
C
NO
CALC P = P + \P D = D + \D
B8
XMTG LAYER
B
10
TOPSIDE Es RFLCTN?
YES
CALC P = P + \P D = D + \D
B6
RFLCTG Es LAYER
C
NO
T
12
11
DID RAY PENETRATE FOR ENTIRE RANGE OF T.O ANGLE?
YES
SEARCH TABLE FOR IDENTICAL MODES BRACKETING RX RANGE
INTERPOLATE T.O ANGLE WITH RESPECT TO RANGE AND SET PROPER FREQ
IF RFLCTN HT DESIRED. TURN ON APPROP. PRGM TOGGLES
NO
2
12
NO
14
CALC TIME DELAY, ATTENUATION, ETC. AND STORE FOR PRINTING
WRITE RFLCTN HT INFO IF REQUESTED
LAST SET OF LIKE MODES IN TABLES?
WRITE STORED RAY INFO FOR EACH MODE
1
15

For each frequency of the specified frequency range, rays are traced from the transmitter for all take-off angles of the specified take-off angle range. A ray is traced until it falls within ±1000 km of the receiver, each reflection from a layer being recorded, in coded form, in a "reflection index". A maximum of ten reflections per ray is allowed. When a ray falls beyond the receiver range +1000 km, tracing of that ray is terminated, the reflection index and accumulated values of P' and D are restored to zero and the next ray of the series is traced. When the ray falls within ±1000 km of the receiver range its reflection index is stored in a table, along with P' and D for that particular ray, and the next ray of the series is traced.

Once all rays for a given frequency have been traced, the table of reflection indices is searched for rays of like modes, a linear interpolation of take-off angle with respect to the actual range of the ray and the range of the receiver is performed, and a new ray with the interpolated take-off angle is traced. At this time the height of the ray at its reflection points is calculated in addition to an estimate of D-layer attenuation. (These equations appear in Appendixes D and E, respectively.) If this new ray does not fall within ±100 km of the receiver, it is ignored and the next pair of like rays (if any) is considered. If it falls within ±100 km of the receiver, its delay time is calculated from

$$\text{Delay time (ms)} = \frac{P' - (\text{Receiver Range} - D)}{300.0} \qquad (12)$$

and the final results are printed. The next pair of like rays (if any) in the table is then considered.

The printed output (Table 3) for each mode consists of the path parameters, the reflections that take place for the mode in "decoded" form, the frequency, take-off angle, ground range, and delay time for the mode. A list of heights

vs range for the reflection points on the path is printed if this information is requested of the program (Table 4).

This process continues for each frequency in the specified range until the frequency range is exhausted or until some frequency in the range fails to propagate any rays between the transmitter and receiver. At this point new ionospheric and/or new path data may be read into the program and the process may be repeated.

B. PROGRAM DETAILS

The ray-tracing program is written in the FORTRAN II computer language, specifically for an IBM 7090 data-processing system. With modifications to the input/output statements, the program could probably be adapted, with little trouble, to other systems such as the IBM 709, CDC 1604, etc. The program requires two magnetic-tape units, one designated logical unit 11 and the other designated as logical 6. The tape on logical unit 11 serves as an input tape and the tape on logical unit 6 is the output tape.

Data for the ray-tracing program are prepared by a second program, which shall be referred to as the "data program". The data program requires, as its input, tables of f_oF_2 and M 3000 factor coefficients for the month for which ray tracing is to be done, in addition to parameters associated with the paths which are to be ray-traced. The output of the data program is a magnetic tape that is used as the input tape for the ray-tracing program.

The tables of f_oF_2 and M 3000 factor coefficients (Dsk) may be obtained in punched-card form from the Bureau of Standards CRPL at Boulder, Colorado. (See CRPL Ionospheric Predictions, Handbook 90. [Ref. 18]) These tables also contain the sunspot number for the month.

The data program will also accept as input, actual measured values of f_oF_2- and F_2-layer real height as a function of their position on the path, to be used by the ray-tracing program.

Appendix F contains listings of the FORTRAN source programs for both the data and ray-tracing programs in addition to sample output from the ray-tracing program which has already appeared as Tables 2,3, and 4, and sample input for the data program.

C. OPTIONS AVAILABLE ON THE DATA PROGRAM

In preparing data for paths to be ray traced for a given month, the tables (on cards) of D_{sk} need be read only once by the program. When the program reads the D_{sk} tables from cards it places them on magnetic tape (logical unit 10), in binary form, where they are available for future use.

Normally, ray tracing is done over a given path, for a 24-hour period, once each hour: however, provisions have been made in the data program to allow tracing for an arbitrary number of selected times (at most 100) on any given path. The number of times to be traced is specified to the program, followed by the actual times to be used. For example, in the normal case 24 times would be specified followed by each hour from 0 through 23.

When empirical data are to be used for ray tracing a given path, that is, ionosonde records of f_oF_2- and F_2-layer real heights, even though the CRPL tables of D_{sk} are not used, the D_{sk} tape must be mounted on unit 10 nonetheless. These empirical data are presented to the data program in the form of f_oF_2- and F_2-layer height as a function of distance along the great-circle path, measured in kilometers from the transmitter. There must be an odd number of measurement points specified.

Sporadic-E data may also be included when the empirical data form is used. No provisions have been made to include sporadic-E when the prediction tables are used. However, this omission may be remedied with only minor difficulty: and procedure will be discussed after a description of the output from the ray-tracing program.

The data program writes a BCD tape on unit 11 which is used as an input tape by the ray-tracing program.

D. INPUT TO AND OUTPUT FROM THE RAY-TRACING PROGRAM

Input to the ray-tracing program is provided by a binary-coded decimal (BCD) tape written by the data program. It is to be mounted on unit 11. Output from the ray-tracing program consists of an ionospheric profile (Table 2), constructed from either the CRPL predictions or empirical data, at 100-km intervals along the path; path identification information such as the name or number of the path, the time, month and day for which the tracing is being done, etc. The actual path-identification information used is up to the user and will be explained in the section on the preparation of input cards for the data program.

The length of the great-circle path between the transmitter and receiver, the latitude and longitude of the transmitter (Tx), the bearing from the transmitter to the receiver are all printed and labeled for each time a series of rays is traced. (In the normal case, once each hour for the 24-hour period.)

Actual information concerning the rays traced appears in Table 3 under the following column headings, with the associated definitions:

MODE: The mode structure of the ray propagated between the transmitter and receiver. The symbol "·E" indicates a ray reflection from the bottom side of the E layer. The symbol "-E" indicates a ray

reflection from the top side of the E layer. The same definitions apply to E_s F_1, and F_2 layers. Obviously, "$-F_2$" is not defined and will not occur.

FREQ: The frequency (in megacycles) of the ray traced.

BETA: The take-off angle (in degrees) of the ray traced.

DIST: The actual ground distance (in kilometers) the ray travels between transmitter and receiver. Because of inaccuracies in the ray-tracing technique this distance will, in general, not be equal to the actual path length.

TIME: The delay time (in milliseconds) of the ray traced, corrected to the actual path length.

DIFF: The difference (in kilometers) between the ground distance the ray travels and the actual path length.

DB: The attenuation, (in decibels) the ray experiences due to D layer absorption only.

Information concerning reflection heights of the rays is also printed (Table 4), but only if it is specifically requested of the program. The details for obtaining this information are discussed in the next section.

If the reflection-height information is requested it appears in the following form: the path parameters and identification are printed, the MODE is specified (as above), along with the ray frequency and take-off angle. The heights appear under a column headed HEIGHT and the corresponding range appears under a column headed RANGE; both are in kilometers.

In all cases an ionospheric profile along the path is printed prior to the printing of any other information. It consists of the path-identification information and columns headed FOE, FOF1, FOF2, HT FOF2 and RANGE. The f_o values are in megacycles and the f_oF_2 height column is in kilometers, as are the ranges. The range is measured from the transmitter end of the path, and the values fall on the great circle between the transmitter and receiver. The path parameters printed consist of the PATH LENGTH, TX LAT (transmitter latitude), TX LONG (transmitter longitude),

and RX BEARING (the great-circle bearing from the transmitter to the receiver).

In order to provide sporadic-E information on ray tracings that make use of the CRPL prediction tables, it is necessary, first, to accomplish the required tracings without E_s data, and then, using the f_oF_2- and F_2-layer real-height information provided by the ray-tracing program, resubmit this information to the data program in the empirical-data format, along with the required E_s data. This technique was adopted in the interest of programming simplicity and, since the inclusion of E_s is usually done on an "after-the-fact" basis, it would seem a justifiable approach.

E. INPUT-CARD FORMATS FOR THE DATA PROGRAM

1. First Card

The first card of every data set contains the program variables called IDATA, IDSKC, IEND, in that order. This card is read under a FORTRAN format of (3I2). The value of each of these variables may be "1" or "0" (zero).

If IDATA = 1: Data are to be supplied to the program in the empirical format.

If IDATA = 0: Data are to be supplied to the program in the form to make use of the CRPL D_{sk} tables.

If IDSKC = 1: The D_{sk} tables for the month in question have not yet been put on magnetic tape and immediately follow this first card.

If IDSKC = 0: The D_{sk} tables for the month in question are on magnetic-tape unit 10.

If IEND = 1: An END OF FILE mark is to be written immediately on magnetic-tape unit 11 and program execution is to be terminated.

If IEND = 0: Additional sets of path data follow.

2. Cards for Program Using D_{sk} Tables

The following cards constitute the information required to generate data for the ray-tracing program using the D_{sk} tables:

Card #1: Contains the program variables TXLAT, TXLON, RXLAT, RXLON, SUNDEC.

TXLAT: The latitude of the transmitting point in degrees and hundredths of degrees. North latitude is +; South latitude is -. Format F7.2.

TXLON: The longitude of the transmitting point in degrees and hundredths of degrees. East longitude is +; West longitude is -. Format F8.2.

RXLAT: The latitude of the receiving point. Same as TXLAT.

RXLON: The longitude of the receiving point. Same as TXLON.

SUNDEC: The declination of the sun in degrees, Format F7.2.

This information is obtained from the Nautical Almanac.

Card #2: Contains the program variables FREQL, FREQD, FREQH, ANGLL, ANGLD, ANGLH.

FREQL: The lowest frequency to be traced, in megacycles. Format F7.3.

FREQD: The frequency increment to be used between the lowest frequency and highest frequency, in megacycles. Format F7.3.

FREQH: The highest frequency to be traced, in megacycles. Format F7.3.

ANGLL: The lowest take-off angle to be traced, in degrees. Format F7.3.

ANGLD: The take-off angle increment to be used between the lowest angle and highest angle, in degrees, Format F7.3.

ANGLH: The highest take-off angle to be traced, in degrees. Format F7.3

Card #3: Contains the program variables NTIMES.

NTIMES: The number of specific times of day to be used by the ray-tracing program for the path described. $0 < \text{NTIMES} \leq 100$. Format I3.

Card Set #4: Contains the program variable TIME (I). One card for each value of TIME (), in GMT, to be used. The number of cards must correspond to NTIMES. Format F6.2.

Card #5: Contains the program variable NCHT. NCHT is

the number of discrete frequencies for which detailed ray-reflection-height information is desired. If no such information is desired, NCHT = 0. Format I4. $0 \leq$ NCHT ≤ 50.

Card Set #6: Contains the program variable HFREQ (I), I = 1, 2,... NCHT. There are NCHT cards in this set, each containing a discrete frequency for which ray-reflection-height-information is required. If NCHT = 0 there are no cards in this set. Note - frequencies specified must correspond to frequencies specified to be traced by the program. Format F7.3.

Card Set #7: Contains alpha-numeric data in columns 1 thru 60 for identification purposes. One card must appear for each time used. The actual information used is at the user's discretion.

Additional sets of path data may follow, providing each set is prefaced by a card as described in Sec. 1.

A card of the type described in Sec. 1 with IEND = 1 should immediately follow the last set of path data.

3. Cards for Program Using Real-Height Measurements

The following cards constitute the information required to generate data for the ray-tracing program using actual measurements of f_oF_2- and F_2-layer real height. Remember, it is necessary to have the D_{sk} tape mounted on unit 10, even though the D_{sk} tables are not used!

A card as described in Sec. 1 with IDATA = 1.

Card #1: Same as card #1, Sec. 1.

Card #2: Same as card #2, Sec. 1.

Card #3: Contains the program variable NSETS. NSETS: The number of sets of empirical data, for the path described by cards #1 and #2, to be read. $0 <$ NSETS. Format I3.

Card #4: Same as Card #7 of Sec. 1.

Card #5: Contains the program variables NPTS, SSN, HOUR.

NPTS: The number of measurements along the path as described by cards #1 and #2.

$3 \leq$ NPTS ≤ 100 and must be odd. Format I3.

SSN: Sunspot number. Format F5.1.

HOUR: The time, in GMT, of the measurements. Format F6.2.

Card Set #6: Contains the program variables AFOF2(I), AHT(I), DIST(I). I = 1, 2, ... NPTS.

AFOF2(I): f_oF_2 in megacycles at the point I. Format F6.2.

AHT(I): Real height of the F_2 layer maximum at the point I, in kilometers. Format F7.2.

DIST(I): The distance from the transmitter along the great-circle path to the point I, in kilometers. The first measurement must be at the transmitter (DIST (1) = 0) and the last measurement must be at the receiver (DIST (NPTS) = path length). Format F9.2.

Card #7: Contains the program variable IES.

If IES = 0, no E_s data are to be considered.

If IES = 1, E_s data immediately follow. Format I3.

4. Cards for Program Using Sporadic E Data

Card #1: Contains the program variable NPATCH.

NPATCH: The number of sporadic E patches on the path this particular time. $0 < \text{NPATCH} \leq 10$. Format I4.

Card Set #2: Contains the program variables PSTART(I), PEND(I), I = 1, 2,...NPATCH.

PSTART(I): The distance from the transmitter, along the great-circle path, of the starting point of E_s patch number I.

PEND (I): The distance from the transmitter, along the great-circle path, of the ending point of E_s patch number I. Format 1X, 2F9.2.

Card #3: Contains the program variable NPT.

NPT: The number of f_oE_s values to be read in for patch number "I". $0 < \text{NPT} \leq 10$. Format I4.

Card Set #4: Contains the program variables ESDIST (I,J), TFOES (I,J) I = 1, 2....NPATCH, J = 1, 2,...NPT.

ESDIST (I,J): The distance from the transmitter along the great-circle path to the point (I,J). Note that ESDIST (I,1) must=PSTART(I) and ESDIST(I,NPT) must = PEND (I).

TFOES(I,J): f_oE_s at the point (I,J). Format 1X, 2F9.2.

F. DATA-SET EXAMPLES

Three sets of examples are included at the end of this report to illustrate graphically the preparation of data sets in the form described above in Sec. E.

G. PROGRAMS

Card decks of the FORTRAN source programs for both the data and ray-tracing programs are available from the Stanford Radioscience Laboratory.

H. RUNNING THE PROGRAMS

To run the data program, prepare the appropriate data-input deck in the appropriate format, and submit this with the 7090 binary deck for the data program, along with the appropriate control cards for the FORTRAN MONITOR in use. (This varies with the 7090 installation.) Specify the tapes to be mounted on logical units 10 and 11. Naturally, if D_{sk} tables are to be read from tape, a specific tape must be mounted on unit 10. At the end of the run, unit 11 will contain the input data to be used by the ray-tracing program.

To run the ray-tracing program, mount the appropriate data tape on logical unit 11. Submit the 7090 binary deck for the ray-tracing program along with the appropriate FORTRAN MONITOR control cards. Output from this program appears on the "normal" FORTRAN output tape unit 6.

Neither program makes use of any sense switches or other console features.

VII. CONCLUSIONS

In describing the reasons why the Kift-Fooks technique was chosen, how it would be used in the analysis of propagation data, and giving details of the program for use on a high-speed digital computer, no comparisons were made with actual records taken. It remained the intention of the authors to outline the work done here at Stanford and their reasons for doing it.

Comparison of ray tracings with experimental data has been done on several paths and the results of these comparisons are scheduled for another report.

Hopefully, the reader of this report will find sufficient information to enable him to reproduce this version of the ray-tracing program for use on available computers should he desire to do so. Duplicate decks of the program can be obtained from the authors by written request.

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APPENDIX A. TERMINOLOGY

This Appendix has been taken directly from the "Report of the Lindau Meeting on Oblique Sounding of the Ionosphere," May 6-10, 1963. The recommendations listed below are to be submitted to URSI and are also scheduled to be published in the IQSY notes.

It was recognized that, for purposes of data interchange, a need exists for the standardization of certain terms. As a first step in this direction, the following recommendations are made.

1. Capital letters should be used in oblique-incidence work in contrast to the small letters agreed upon in vertical-incidence work.
2. In view of the ambiguity in the meaning of << usable >>, the term maximum usable frequency (MUF) should be eliminated in the description of oblique-incidence ionograms.
3. The use of the word "virtual path" should refer to the time of flight (group delay) in oblique propagation work.
4. In ray tracing the following symbols are suggested (Fig. A1).
    a. ϕ_o the angle of incidence at the bottom of the ionosphere.
    b. ϕ_r the angle of incidence, at the real height of reflection, of the extension of the linear ray path below the ionosphere.
    c. i the angle between the ray path and the vertical at any point along the path.
    d. Δ the angle of elevation at the ground.

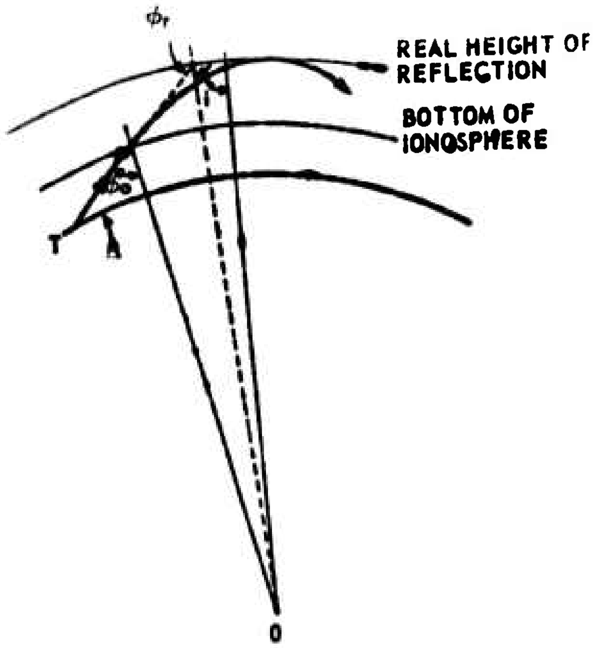

FIG. A1 RECOMMENDED RAY-PATH GEOMETRY.

The following terminology is suggested for the description of path structure (Fig. A2).

5. For propagation paths involving reflections by different layers, the reflections (or hops) should be specified in order of their position with respect to the transmitter. Thus 5E - 3F2 indicates five reflections from the E layer near the transmitter followed by three reflections from the F2 layer (Fig. A2-a).

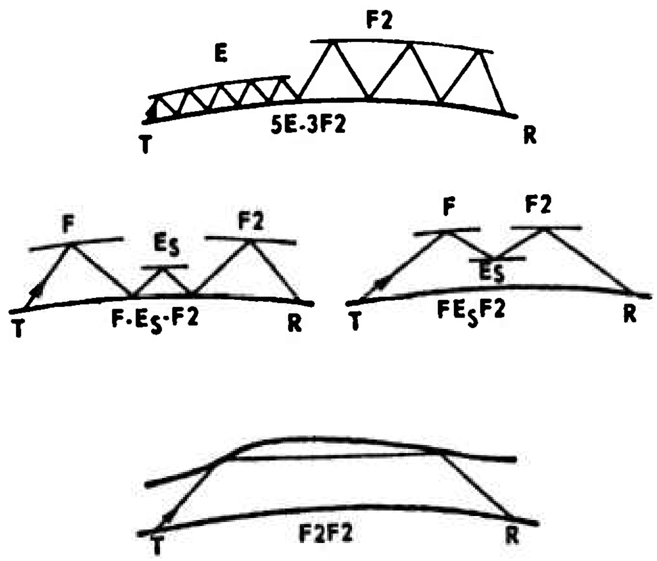

FIG. A2 RECOMMENDED MODE IDENTIFICATION.

6. The use of a dash is convenient for the representation of a ground reflection. The absence of a dash will then show up M-type ray paths and "supermodes." example F - E_s - F2 (Fig. A2-b) represents an F-layer hop followed by ground reflection to the lower side of the E_s layer, reflection back to ground, then reflection to the lower side of the F2 layer and finally back to ground. On the other hand F E_s F2 (Fig. A2-c) represents an M-type path in which the ray is reflected from the F layer to the upper side of the $E_{\bar{o}}$ layer, back up to the lower side of the F2 layer and down to the ground. The symbol F2F2 (Fig. A2-d) means an F2 reflection followed by another F2 reflection without an intermediate ground reflection (supermode).

The following terms are suggested for the description of oblique ionograms (Fig. 13).

7. MOF (Maximum Observed Frequency) means the highest frequency on which the sounder-transmitter signals are observed on the ionogram, regardless of the propagation path involved.

8. LOF (Lowest Observed Frequency) means the lowest frequency on which the sounder-transmitter signals are observed on the ionogram, regardless of the propagation path involved.

9. These terms (MOF and LOF) may be used also to describe identifiable modes. For example 2F2 LOF means the lowest frequency (observed on the ionogram) which is propagated by two reflections at the F2 layer and an intermediate ground reflection. The 2F2 MOF means the highest observed frequency associated with two-hop F2 propagation, regardless of whether the signal is propagated by refraction, by scatter, or by a combination of both mechanisms.

10. The lowest observed frequency of the high-angle ray may be distinguished from that of the low-angle ray by the letters H and L respectively. Thus 2F2 HLOF is the lowest frequency (observed on the ionogram) of the signal that is propagated via the high-angle, two-hop, F2 path and 2F2 LLOF is the lowest frequency (observed on the ionogram) of the signal that is propagated by the low-angle, two-hop, F2 path.

11. The one-hop modes do not need the number 1(one) in front. For example, F2 LLOF means the low-angle ray LOF for the one-hop, F2 ray path.

12. When it is required to distinquish between the ordinary and extraordinary ray paths an "o" or "x" may follow in parentheses. The F2 MOF(x) is the maximum observed frequency of the extraordinary wave that is reflected once at the F2 layer.

13. Often the MOF for an identifiable path is greater than the frequency on which the regularly refracted components of the high-and low-angle rays join. It is suggested that the latter frequency be called the "junction frequency" and that it be denoted by JF.

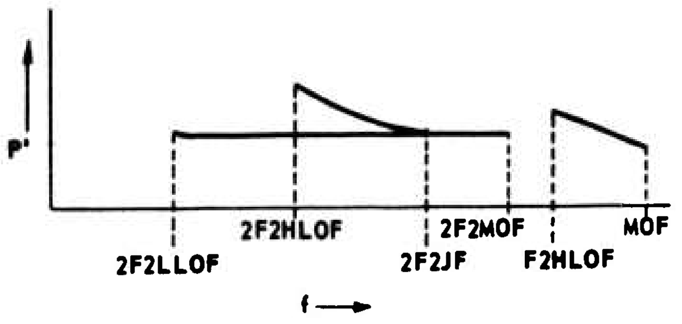

FIG. A3 RECOMMENDED IONOGRAM-SCALING PARAMETERS.

APPENDIX B. CALCULATION OF THE SUN'S ZENITH ANGLE, χ

$$\cos \chi = \sin \lambda_1 \sin \lambda_2 + \cos \lambda_1 \cos \lambda_2 \cos \left(\theta_2 - \theta_1\right)$$

$$\sin \lambda_1 = \sin \lambda_o \cos \left(\frac{d}{R}\right) + \cos \lambda_o \sin \left(\frac{d}{R}\right) \cos \alpha$$

$$\cot \left(\theta_1 - \theta_o\right) = \left[\sin \lambda_o \cos \alpha - \cos \lambda_o \cot \left(\frac{d}{R}\right)\right] \sin \alpha$$

$$\theta_2 = \left[\frac{(T-12)}{24}\right] \cdot 2\pi \text{ (neglecting equation of time)} \qquad (B.1)$$

where

λ_o = latitude of transmitter

θ_o = longitude of transmitter

T = time in hours (U.T.)

λ_2 = declination of sun

α = bearing E. of N. of receiver from transmitter

θ_2 = longitude of sun

λ_1 = latitude of point on path

θ_1 = longitude of point on path

d = distance from transmitter to point on path

R = radius of earth

The data program computes α and the path length, using the latitude and longitude of both the transmitting and receiving points and supplies the ray-tracing program with these parameters, in addition to the latitude and longitude of the transmitter. The data program also supplies a set of distances d_i at roughly every 500 km along the path at which f_oF2 and F2 4000 MUF are supplied by the data program.

APPENDIX C. A METHOD FOR COMPUTING F2 LAYER HEIGHT h_m FROM VALUES OF f_oF_2 AND F2 4000 MUF

A nomogram of height h_m versus the ratio of F2 4000 MUF and f_oF2 for a parabolic layer with $Y_m = 0.4\ h_o$ is presented in the Fooks report [Ref. 12]. A polynomial expression, valid for

$$2.15 \le \frac{\text{F2 4000 MUF}}{f_oF2} \le 4.09, \tag{C.1}$$

which approximates the nomogram with maximum error in h_m of $\pm$ 6 km, is used in the program to compute h_m.

$$\text{Let } x = \frac{\text{F2 4000 MUF}}{f_oF2} = 1.1\ (\text{M3000}),$$

$$h_m = \left(\frac{2218.59}{x^{1.7083}}\right) + 19.44\ (4.09 - x)\ (x - 2.15) + 46.0\ (3.0 - x)\ (4.09 - x)\ (x - 2.15) \tag{C.2}$$

APPENDIX D. CALCULATION OF REFLECTION HEIGHTS OF THE RAY IN A LAYER

The height of reflection h_r is calculated as follows:

$$h_r = h_o + Y_m \left[1 - \sqrt{1 - \left(\frac{f}{f_o} \cos i\right)^2}\right] \tag{D.1}$$

in the case of a ray reflecting from the bottom of a layer, and

$$h_r = h_o + 2Y_m - Y_m \left[1 - \sqrt{1 - \left(\frac{f}{f_o} \cos i\right)^2}\right] \tag{D.2}$$

in the case of a ray reflecting from the top of a layer.

The definition of the parameters is the same as in Eqs. (4) and (5).

APPENDIX E. CALCULATION OF RAY ATTENUATION DUE TO D-LAYER ABSORPTION

The following expression, taken from RPU No. 9 [Ref. 21] is an estimate of the absorption in the D layer

$$DB = \frac{615.5\,(1.0 + 0.0037\cdot SSN)\ .\ \cos^{1.3}(0.881\chi)\cdot N\cdot \sec\varphi_D}{(f + f_h)^{1.98}} \tag{E.1}$$

where

SSN = sunspot number

χ = sun's zenith angle

N = number of ray passages through the D layer

f = ray frequency

φ_D = vertical angle which ray makes with the D layer

f_h = gyro-frequency

DB = number of decibels of ray attenuation

In the ray-tracing program the D layer is assumed to be at a height of 70 km. This height plus ray take-off angle allows the calculation of φ_D. Since the program assumes a constant ray take-off angle, this quantity φ_D is computed only once for each mode. An average value of $\cos\chi$ is used for each mode and an average value of f_h along the path is used in the calculation.

APPENDIX F. LISTING OF DATA AND RAY-TRACING PROGRAMS, SAMPLE OUTPUT AND INPUT FORMATS

The following figures consist of sample input data for the data program, a listing of the data program, a listing of the ray-trace program, and sample output from the ray-trace program.

```
EXAMPLE NUMBER 1...RAY TRACINGS ARE DESIRED FOR THE MONTH OF JUNETEMBER
       BETWEEN A TRANSMITTER LOCATED AT 122.59 DEGREES WEST
       LONGITUDE AND 37.56 DEGREES NORTH LATITUDE AND A
       RECEIVER LOCATED AT 15.75 DEGREES EAST LONGITUDE AND
       23.22 DEGREES SOUTH LATITUDE.THE RAY TRACING IS TO
       BE ACCOMPLISHED FOR THE FULL 24 HOUR PERIOD.

       IN ADDITION, RAY TRACINGS ARE DESIRED BETWEEN A
       TRANSMITTER AT 159.25 W. 92.55 N AND A RECEIVER AT
       72.50 W. 47.55 N. FOR THE HOURS 0900,1200,1500,1650
       GMT.

       IN BOTH CASES THE FREQUENCY RANGE TO BE TRACED IS
       4 TO 32 MC/S IN 2 MC/S STEPS. IN THE FIRST CASE TAKE-
       OFF ANGLES BETWEEN 0 AND 25 DEGREES, IN STEPS OF
       1 DEGREE WILL BE CONSIDERED. IN THE SECOND CASE
       TAKE-OFF ANGLES BETWEEN 4.25 AND 10.25 DEGREES,IN
       STEPS OF 0.25 DEGREES WILL BE CONSIDERED.

       THE NAUTICAL ALMANAC GIVES THE SUN DECLINATION
     AS -18.69 DEGREES FOR THE 15 TH DAY OF THE MONTH OF
     JUNETEMBER.

       THE TABLES OF DSK FROM CRPL HAVE NOT YET BEEN PUT
       ON TAPE.

       IN THE FIRST CASE, RAY HEIGHT INFORMATION IS
       DESIRED AT 8, 14, 16 AND 22 MC/S.
       IN THE SECOND CASE, NO RAY HEIGHT INFORMATION IS
       DESIRED.

 THE TABLES OF DSK ARE INSERTED HERE, THE DSK FOR FOF2 FIRST.
 IMMEDIATELY FOLLOWED BY THE DSK FOR THE M3000 FACTOR

  37.56 -122.59 -23.22   15.75 -18.69
  4.0   2.0   32.0   0.0   1.0   25.0
 24
   .0
  1.0
  2.0
  3.0
  4.0
  5.0
  6.0
  7.0
  8.0
  9.0
 10.0
 11.0
 12.0
 13.0
 14.0
 15.0
 16.0
 17.0
 18.0
 19.0
 20.0
 21.0
 22.0
 23.0
```

```
8.0
14.0
16.0
22.0
THIS IS AN EXAMPLE SET OF DATA FOR JUNETEMBER 0000 GMT
THIS IS AN EXAMPLE SET OF DATA FOR JUNETEMBER 0100 GMT
THIS IS AN EXAMPLE SET OF DATA FOR JUNETEMBER 0200 GMT
THIS IS AN EXAMPLE SET OF DATA FOR JUNETEMBER 0300 GMT
THIS IS AN EXAMPLE SET OF DATA FOR JUNETEMBER 0400 GMT
THIS IS AN EXAMPLE SET OF DATA FOR JUNETEMBER 0500 GMT
THIS IS AN EXAMPLE SET OF DATA FOR JUNETEMBER 0600 GMT
THIS IS AN EXAMPLE SET OF DATA FOR JUNETEMBER 0700 GMT
THIS IS AN EXAMPLE SET OF DATA FOR JUNETEMBER 0800 GMT
THIS IS AN EXAMPLE SET OF DATA FOR JUNETEMBER 0900 GMT
THIS IS AN EXAMPLE SET OF DATA FOR JUNETEMBER 1000 GMT
THIS IS AN EXAMPLE SET OF DATA FOR JUNETEMBER 1100 GMT
THIS IS AN EXAMPLE SET OF DATA FOR JUNETEMBER 1200 GMT
THIS IS AN EXAMPLE SET OF DATA FOR JUNETEMBER 1300 GMT
THIS IS AN EXAMPLE SET OF DATA FOR JUNETEMBER 1400 GMT
THIS IS AN EXAMPLE SET OF DATA FOR JUNETEMBER 1500 GMT
THIS IS AN EXAMPLE SET OF DATA FOR JUNETEMBER 1600 GMT
THIS IS AN EXAMPLE SET OF DATA FOR JUNETEMBER 1700 GMT
THIS IS AN EXAMPLE SET OF DATA FOR JUNETEMBER 1800 GMT
THIS IS AN EXAMPLE SET OF DATA FOR JUNETEMBER 1900 GMT
THIS IS AN EXAMPLE SET OF DATA FOR JUNETEMBER 2000 GMT
THIS IS AN EXAMPLE SET OF DATA FOR JUNETEMBER 2100 GMT
THIS IS AN EXAMPLE SET OF DATA FOR JUNETEMBER 2200 GMT
THIS IS AN EXAMPLE SET OF DATA FOR JUNETEMBER 2300 GMT
0 0 0
52.99 -157.25 47.53 -72.50 -18.69
4.0 2.0 52.0 5.25 0.25 10.25
*
```

```
9.0
12.0
14.0
16.5
0
THIS IS AN EXAMPLE SET OF DATA FOR JUNETEMBER 0900 GMT
THIS IS AN EXAMPLE SET OF DATA FOR JUNETEMBER 1200 GMT
THIS IS AN EXAMPLE SET OF DATA FOR JUNETEMBER 1500 GMT
THIS IS AN EXAMPLE SET OF DATA FOR JUNETEMBER 1830 GMT
0 0 1
```

```
EXAMPLE NUMBER 2...THIS IS THE SAME AS EXAMPLE NUMBER 1. WITH THE
          EXCEPTION THAT THE DSK TABLES ARE ASSUMED TO BE ON
          MAGNETIC TAPE TO START WITH

 0 0 0
 57.56 -122.55 -23.22  15.75 -18.83
 6.0   2.0   32.0   5.0   1.0   25.0
24
  .0
 1.0
 2.0
 3.0
 4.0
 5.0
 6.0
 7.0
 8.0
 9.0
10.0
11.0
12.0
13.0
14.0
15.0
16.0
17.0
18.0
19.0
20.0
21.0
22.0
23.0
4
8.0
14.0
16.0
22.0
THIS IS AN EXAMPLE SET OF DATA FOR JUNETEMBER 0000 GMT
THIS IS AN EXAMPLE SET OF DATA FOR JUNETEMBER 0100 GMT
THIS IS AN EXAMPLE SET OF DATA FOR JUNETEMBER 0200 GMT
THIS IS AN EXAMPLE SET OF DATA FOR JUNETEMBER 0300 GMT
THIS IS AN EXAMPLE SET OF DATA FOR JUNETEMBER 0400 GMT
THIS IS AN EXAMPLE SET OF DATA FOR JUNETEMBER 0500 GMT
THIS IS AN EXAMPLE SET OF DATA FOR JUNETEMBER 0600 GMT
THIS IS AN EXAMPLE SET OF DATA FOR JUNETEMBER 0700 GMT
THIS IS AN EXAMPLE SET OF DATA FOR JUNETEMBER 0800 GMT
THIS IS AN EXAMPLE SET OF DATA FOR JUNETEMBER 0900 GMT
THIS IS AN EXAMPLE SET OF DATA FOR JUNETEMBER 1000 GMT
THIS IS AN EXAMPLE SET OF DATA FOR JUNETEMBER 1100 GMT
THIS IS AN EXAMPLE SET OF DATA FOR JUNETEMBER 1200 GMT
THIS IS AN EXAMPLE SET OF DATA FOR JUNETEMBER 1300 GMT
THIS IS AN EXAMPLE SET OF DATA FOR JUNETEMBER 1400 GMT
THIS IS AN EXAMPLE SET OF DATA FOR JUNETEMBER 1500 GMT
THIS IS AN EXAMPLE SET OF DATA FOR JUNETEMBER 1600 GMT
THIS IS AN EXAMPLE SET OF DATA FOR JUNETEMBER 1700 GMT
THIS IS AN EXAMPLE SET OF DATA FOR JUNETEMBER 1800 GMT
THIS IS AN EXAMPLE SET OF DATA FOR JUNETEMBER 1900 GMT
THIS IS AN EXAMPLE SET OF DATA FOR JUNETEMBER 2000 GMT
THIS IS AN EXAMPLE SET OF DATA FOR JUNETEMBER 2100 GMT
THIS IS AN EXAMPLE SET OF DATA FOR JUNETEMBER 2200 GMT
THIS IS AN EXAMPLE SET OF DATA FOR JUNETEMBER 2300 GMT
0 0 0
 32.55 -157.25  47.55  -72.50 -20.65
 6.0   2.0   32.0   5.25   0.25  10.25
```

```
8
9.0
37.0
35.0
36.0
0
THIS IS AN EXAMPLE SET OF DATA FOR JUNETEMBER 0900 GMT
THIS IS AN EXAMPLE SET OF DATA FOR JUNETEMBER 1200 GMT
THIS IS AN EXAMPLE SET OF DATA FOR JUNETEMBER 1500 GMT
THIS IS AN EXAMPLE SET OF DATA FOR JUNETEMBER 1830 GMT
0 0 1
```

```
EXAMPLE NUMBER 3...RAY TRACINGS ARE DESIRED BETWEEN A TRANSMITTER
                   LOCATED AT 122.59 W. 37.56 N AND A RECEIVER LOCATED
                   AT 15.75 E. 23.22 S. VERTICAL IONOSPHERIC SOUNDINGS
                   ARE AVAILABLE ALONG THE GREAT CIRCLE PATH FOR THE
                   HOURS 0615.1030.1245 AND 1430. GMT. OF THE DAY IN
                   QUESTION. THERE ARE 5 SETS OF VERTICAL SOUNDINGS.
                   THE FIRST IS TAKEN AT THE TRANSMITTER. THE SECOND
                   1000 KM FROM THE TRANSMITTER. THE THIRD 3750 KM FROM
                   THE TRANSMITTER. THE FOURTH 6300 KM FROM THE
                   TRANSMITTER. AND THE FIFTH AT THE RECEIVER. THE TABLE
                   BELOW DESCRIBES THE MEASUREMENTS.

                         FOR 0615 GMT
                   RANGE    FOF2    HMF2(F2 LAYER MAX HEIGHT)
                       0     4.9    223.0
                    1000     6.2    245.0
                    3750     7.4    230.0
                    6300     7.8    255.0
                      RX     8.0    260.0

                         FOR 1030 GMT
                   RANGE    FOF2    HMF2(F2 LAYER MAX HEIGHT)
                       0     8.2    220.0
                    1000    10.5    235.0
                    3750    11.7    230.0
                    6300    12.0    225.0
                      RX    12.5    227.0

                         FOR 1245 GMT
                   RANGE    FOF2    HMF2(F2 LAYER MAX HEIGHT)
                       0    11.8    237.0
                    1000    12.2    240.0
```

```
3750    11.7    235.0
6300    10.4    232.0
RX      9.5     225.0

            FOR 1430 GMT
RANGE   FOF2    HMF2(F2 LAYER MAX HEIGHT)
   0    12.5    240.0
2000    11.5    238.0
3750    11.3    235.0
6300    10.0    230.0
  RX     9.0    228.0

THE RECEIVER RANGE, RX, IS ABOUT 9000 KM.
TWO DISTINCT PATCHES OF SPORADIC E ARE NOTED ON THE
RECORDS FOR 1245 GMT. ONE STARTS AT ROUGHLY 1200 KM
AND ENDS AT 2000 KM. THE SECOND STARTS AT 6400 KM
AND ENDS AT 7000 KM. THE CRITICAL, FOES, FOR THE
FIRST PATCH IS ROUGHLY CONSTANT AT 6.0 MC/S. AND THE
CRITICAL FOR THE SECOND PATCH IS ROUGHLY CONSTANT
AT 7.2 MC/S. NO SPORADIC E IS NOTED ON THE OTHER
RECORDS.

THE SUNSPOT NUMBER FOR THE MONTH IS 32 AND THE SUN
DECLINATION IS 8.32 DEGREES.

A FREQUENCY RANGE OF 4 TO 32 MC/S. IN 1 MC/S STEPS
IS TO BE TRACED, AND TAKE-OFF ANGLES BETWEEN 5 AND
20 DEGREES, IN 0.5 DEGREE STEPS ARE TO BE CONSIDERED

RAY HEIGHT INFORMATION IS DESIRED AT 6, 7, 8, 20,
AND 25 MC/S.
```

```
1 0 0
37.56 -122.53 -23.22   15.75   9.92
4.0    1.0    32.0    5.0    0.5    20.0
5
6.0
7.0
8.0
20.0
25.0
4
PATH FOR 0615 GMT. SOUNDER DATA, NO SPORADIC E
5 32.0  6.25
4.50 223.00      0.00
6.20 245.00   1000.00
7.40 260.00   3750.00
7.80 255.00   6300.00
8.00 260.00   9000.00
0
PATH FOR 1030 GMT. SOUNDER DATA, NO SPORADIC E
5 32.0 10.50
8.20 220.00      0.00
10.50 235.00  1000.00
11.70 290.00  3750.00
12.00 225.00  6300.00
12.50 227.00  9000.00
0
PATH FOR 1245 GMT. SOUNDER DATA, SPORADIC E PRESENT
5 32.0 12.75
11.00 237.00     0.00
12.20 240.00  1000.00
11.70 295.00  3750.00
10.40 290.00  6300.00
```

```
9.50 225.00  9000.00
1
2
 1200.00  2000.00
 6400.00  7000.00
 3
 1200.00     6.00
 1600.00     6.00
 2000.00     6.00
 4
 6400.00     7.20
 6600.00     7.20
 6800.00     7.20
 7000.00     7.20
PATH FOR 1430 GMT. NO SPORADIC E
 5 32.0 14.50
12.50 240.00      0.00
11.50 238.00   1000.00
11.30 235.00   3750.00
10.00 230.00   6300.00
 9.00 228.00   9000.00
 0
0 0 1
```

```
C     DATA PREPARATION PROGRAM FOR RAY TRACE PROGRAM
      FUNCTION GKA(SX,SY,S2Y,CX,CY,C2Y,KA,K,L,1)
      IF(KA-K) 1,1,4
    1 IF(KA-1) 3,2,3
    2 GKA=1.0
      RETURN
    3 GKA=SX**(KA-1)
      RETURN
    4 IF(KA-L) 5,5,12
    5 LA=((KA-K)/2)-1
      IF(XMODF((KA-K),2)) 6,9,6
    6 LA=LA+1
      IF(LA) 8,7,8
    7 GKA=CX*CY
      RETURN
    8 GKA=CX*CY*SX**LA
      RETURN
    9 IF(LA) 11,10,11
   10 GKA=CX*SY
      RETURN
   11 GKA=CX*SY*SX**LA
      RETURN
   12 LB=((KA-L)/2)-1
      IF(XMODF((KA-L),2)) 13,16,13
   13 LB =LB+1
      IF(LB) 15,14,15
   14 GKA=C2Y*CX**2
      RETURN
   15 GKA=C2Y*(CX**2)*SX**LB
      RETURN
   16 IF(LB) 18,17,18
   17 GKA=S2Y*CX**2
```

```
C     DATA PREPARATION PROGRAM FOR RAY TRACE PROGRAM
      SUBROUTINE LATLON(TXLAT,TXLON,RXLAT,RXLON,PLKM,AZMTH,PDIST,PLAT,
     1PLON,N)
      DIMENSION PDIST(100),PLAT(100),PLON(100)
      PI=3.1415927
      PIOV2=1.5707963
      TWOPI=6.2831853
      DEGRAD=PI/180.0
      RADDEG=180.0/PI
      R=6367.0
      TXLATR=DEGRAD*TXLAT
      TXLONR=DEGRAD*TXLON
      RXLATR=DEGRAD*RXLAT
      RXLONR=DEGRAD*RXLON
      C=ABSF(TXLONR-RXLONR)
      IF(C-PI) 2,2,1
    1 C=TWOPI-C
    2 AA=PIOV2-TXLATR
      BB=PIOV2-RXLATR
      CC=COSF(AA)*COSF(BB)+SINF(AA)*SINF(BB)*COSF(C)
      ARG=SQRTF(1.0-CC**2)/CC
      ANG=ATANF(ARG)
      IF(ARG) 3,4,4
    3 ANG=ANG+PI
    4 PLKM=111.12*RADDEG*ANG
      COTC=COSF(C/2.0)/SINF(C/2.0)
      AMB=ATANF(COTC*SINF((AA-BB)/2.0)/SINF((AA+BB)/2.0))
      APB=ATANF(COTC*COSF((AA-BB)/2.0)/COSF((AA+BB)/2.0))
      AZMTH=APB-AMB
      IF(TXLON-RXLON) 6,6,5
    5 AZMTH=TWOPI-AZMTH
    6 IF(PLKM-5000.0) 7,7,8
```

```
      RETURN
   18 GKA=S2V*(CX**2)*SX**LB
      RETURN
      END
```

```
7 N=11
  GO TO 11
8 IF(PLKM-15000.0) 9,9,10
9 N=21
  GO TO 11
10 N=31
11 FINC=PLKM/FLOATF(N-1)
   PDIST(1)=0.0
   PLAT(1)=TXLATR
   IF(TXLONR) 12,13,13
12 PLON(1)=TXLONR+TWOPI
   GO TO 14
13 PLON(1)=TXLONR
14 TXLONM=-TXLONR
   SINLAT=SINF(TXLATR)
   COSLAT=COSF(TXLATR)
   SINAZM=SINF(AZMTH)
   COSAZM=COSF(AZMTH)
   DO 24 I=2,N
   D=FLOATF(I-1)*FINC
   SIND=SINF(D/R)
   COSD=COSF(D/R)
   SINL1=SINLAT*COSD+COSLAT*SIND*COSAZM
   ARG1=SQRTF(1.0-SINL1*SINL1)
   ARG2=SINL1/ARG1
   FLAT1=ATANF(ARG2)
   COT=(SINLAT*COSAZM-COSLAT*COSD/SIND)/SINAZM
   ATANG=ATANF(1.0/COT)
   IF(AZMTH-PI) 15,18,18
15 IF(ATANG) 16,17,17
16 THI=TXLONM+ATANG
   GO TO 21
17 THI=TXLONM+(ATANG-PI)
   GO TO 21
18 IF(ATANG) 20,20,19
19 THI=TXLONM+ATANG
   GO TO 21
20 THI=TXLONM+(ATANG+PI)
21 THI=-THI
   IF(THI) 22,23,23
22 THI=THI+TWOPI
23 PDIST(I)=D
   PLAT(I)=FLAT1
24 PLON(I)=THI
   RETURN
   END
```

```
C     DATA PREPARATION PROGRAM FOR RAY TRACE PROGRAM
      DIMENSION CFOF2(60,25),CMUF3(60,25),PDIST(100),PLAT(100),PLON(100)
      DIMENSION NMPATH(10),A(20),B(20),GF(25,60),GM(25,60),TIME(100)
      DIMENSION AFOF2(100), AHT(100),DIST(100),HFREQ(50)
      DIMENSION PSTART(20),PEND(10),ESDIST(10,10),TFOFS(10,10)
      DEGRAD=(3.1415927/180.0)
      RADDEG=(180.0/3.1415927)
    1 REWIND 10
      REWIND 11
    2 READ INPUT TAPE 5,3,IDATA,IDSKC,IEND
    3 FORMAT(3I2)
      IF(IEND-1) 301,35,301
  301 IF(IDATA-1) 4,36,4
    4 IF(IDSKC-1) 10,5,10
    5 READ INPUT TAPE 5,6,NF,NHF,NIF,NIIF,SSN,NS,NK,CFOF2(1,1)
    6 FORMAT(21X,I2,2X,I2,6X,I2,2X,I2,9X,F5.1,3X,I2,3X,I2,3X,E14.7)
      WRITE TAPE 10,NF,NHF,NIF,NIIF,SSN
      NFDSK=((NF+1)*(2*NHF+1))-1
      NK1=NF+1
      NS1=2*NHF+1
      DO 7 I=1,NFDSK
      READ INPUT TAPE 5,8,NS,NK,CFOF2V
      NKP1=NK+1
      NSP1=NS+1
    7 CFOF2(NKP1,NSP1)=CFOF2V
    8 FORMAT(54X,I2,3X,I2,3X,E14.7)
      WRITE TAPE 10,((CFOF2(I,J),J=1,NS1),I=1,NK1)
      READ INPUT TAPE 5,6,NM,NHM,NIM,NIIM,SSN,NS,NK,CMUF3(1,1)
      WRITE TAPE 10,NM,NHM,NIM,NIIM
      NMDSK=((NM+1)*(2*NHM+1))-1
      NK1=NM+1
      NS1=2*NHM+1
      DO 9 I=1,NMDSK
      READ INPUT TAPE 5,8,NS,NK,CMUF3V
      NKP1=NK+1
      NSP1=NS+1
    9 CMUF3(NKP1,NSP1)=CMUF3V
      WRITE TAPE 10,((CMUF3(I,J),J=1,NS1),I=1,NK1)
      END FILE 10
      REWIND 10
      GO TO 11
   10 READ TAPE 10,NF,NHF,NIF,NIIF,SSN
      NK1=NF+1
      NS1=2*NHF+1
      READ TAPE 10,((CFOF2(I,J),J=1,NS1),I=1,NK1)
      READ TAPE 10,NM,NHM,NIM,NIIM
      NK1=NM+1
      NS1=2*NHM+1
      READ TAPE 10,((CMUF3(I,J),J=1,NS1),I=1,NK1)
      REWIND 10
   11 READ INPUT TAPE 5,12,TXLAT,TXLON,RXLAT,RXLON,SUNDEC
   12 FORMAT(2(F7.2,F8.2),F7.2)
      READ INPUT TAPE 5,1201,FREQL,FREQD,FREQH,ANGLL,ANGLD,ANGLH
 1201 FORMAT(6F7.3)
      READ INPUT TAPE 5,13,NTIMES
   13 FORMAT(I3)
      DO 1301 I=1,NTIMES
 1301 READ INPUT TAPE 5,1302,TIME(I)
 1302 FORMAT(F6.2)
      READ INPUT TAPE 5,1303,NCHT
 1303 FORMAT(I4)
      IF(NCHT) 1307,1307,1304
 1304 DO 1305 I=1,NCHT
 1305 READ INPUT TAPE 5,1306,HFREQ(I)
```

```
1306 FORMAT(F7.3)
1307 CALL LATLON(TXLAT,TXLON,RXLAT,RXLON,PLENGT,AZMTH,PDIST,PLAT,PLON,
    1NPTS)
     TXLONM=-TXLON
     RXBER=RADDEG*AZMTH
     READ INPUT TAPE 5,14,NMPATH
  14 FORMAT(10A6)
     HOUR=TIME(1)
     ITCNT=1
     ITYPE=1
     IFH=0
     WRITE OUTPUT TAPE 11,15,NMPATH,ITYPE,PLENGT,TXLAT,TXLONM,RXBER,
    1SSN,SUNDEC,HOUR,NPTS,IFH,(PDIST(I),I=1,NPTS)
  15 FORMAT(10A6,I5/1X,F8.2,1X,F6.2,1X,F7.2,1X,F6.2/1X,F5.1,2X,F6.2,1X,
    1F9.2/1X,I3,I2/(1X,F8.2))
     ITYPE=0
     KF=NIF+1
     LF=NIIF+1
     LIF=NF+1
     KM=NIM+1
     LM=NIIM+1
     IM=NM+1
     LHF=NHF+1
     LHM=NHM+1
     DO 18 I=1,NPTS
     X=PLAT(I)
     Y=PLON(I)
     SX=SINF(X)
     SY=SINF(Y)
     S2Y=SINF(2.0*Y)
     CX=COSF(X)
     CY=COSF(Y)
     C2Y=COSF(2.0*Y)
     DO 16 KA=1,LIF
  16 GF(I,KA)=GKA(SX,SY,S2Y,CX,CY,C2Y,KA,KF,LF,LIF)
     DO 17 KA=1,IM
  17 GM(I,KA)=GKA(SX,SY,S2Y,CX,CY,C2Y,KA,KM,LM,IM)
  18 CONTINUE
  19 DO 31 I=1,NPTS
     GMT=15.0*HOUR-180.0
     T=GMT+RADDEG*PLON(I)
     IF(T-180.0) 21,21,20
  20 T=T-360.0
     GO TO 23
  21 IF(T+180.0) 22,23,23
  22 T=T+360.0
  23 TR=DEGRAD*T
     AO=0.0
     DO 24 KA=1,LIF
  24 AO=AO+CFOF2(KA,1)*GF(I,KA)
     FOF2=AO
     DO 26 J=2,LHF
     A(J)=0.0
     B(J)=0.0
     JSA=2*J-1
     JSB=2*J-2
     DO 25 KA=1,LIF
     G=GF(I,KA)
     A(J)=A(J)+CFOF2(KA,JSA)*G
  25 B(J)=B(J)+CFOF2(KA,JSB)*G
     FJM1=FLOATF(J-1)
  26 FOF2=FOF2+(A(J)*COSF(FJM1*TR)+B(J)*SINF(FJM1*TR))
     AO=0.0
     DO 27 KA=1,IM
```

```
29 A0=A0+CMUF3(KA,1)*GM(I,KA)
   FM3000=A0
   DO 29 J=2,LMM
   A(J)=0.0
   B(J)=0.0
   JSA=2*J-1
   JSB=2*J-2
   DO 28 KA=1,IM
   G=GM(I,KA)
   A(J)=A(J)+CMUF3(KA,JSA)*G
28 B(J)=B(J)+CMUF3(KA,JSB)*G
   FJM1=FLOATF(J-1)
29 FM3000=FM3000+(A(J)*COSF(FJM1*T)+B(J)*SINF(FSM1*TR))
   FM9000=1.1*FM3000*FOF2
   WRITE OUTPUT TAPE 11,90,FOF2,FM3000
90 FORMAT(1X,F5.2,1X,F6.2)
31 CONTINUE
   IES=0
   WRITE OUTPUT TAPE 11,92,IES,FREQL,FREQD,FREQH,ANGLL,ANGLD,ANGLH
92 FORMAT(I3/3F7.3/3F7.3)
   WRITE OUTPUT TAPE 11,3201,NCHT
9201 FORMAT(I4)
   IF(NCHT) 9205,9205,9202
9202 DO 9203 I=1,NCHT
9203 WRITE OUTPUT TAPE 11,9204,NFREQ(I)
9204 FORMAT(F7.3)
9205 ITCNT=ITCNT+1
   IF(ITCNT-NTIMES) 93,93,2
93 HOUR=TIME(ITCNT)
   READ INPUT TAPE 5,14,NMPATH
   WRITE OUTPUT TAPE 11,34,NMPATH,ITYPE,SSN,SUNDEC,HOUR
94 FORMAT(10A6,I5/1X,F5.1,2X,F6.2,1X,F5.2)
   GO TO 19
95 END FILE 11
   REWIND 11
   GO TO 7
96 READ INPUT TAPE 5,12,TXLAT,TXLON,RXLAT,RXLON,SUNDEC
   READ INPUT TAPE 5,1701,FREQL,FREQD,FREQH,ANGLL,ANGLD,ANGLH
   READ INPUT TAPE 5,1909,NCHT
   IF(NCHT) 9601,3603,9601
9601 DO 9602 I=1,NCHT
9602 READ INPUT TAPE 5,1306,NFREQ(I)
9603 ITYPE=2
   CALL LATLON(TXLAT,TXLON,RXLAT,RXLON,PLENGT,AZMTH,PDIST,PLAT,PLON,
   1NPTS)
   TXLONM=-TXLON
   RXBER=RADDEG*AZMTH
37 READ INPUT TAPE 5,38,NSETS
38 FORMAT(I3)
   ISETS=1
   IFM=0
   IES=0
39 READ INPUT TAPE 5,14,NMPATH
   READ INPUT TAPE 5,40,NPTS,SSN,HOUR
40 FORMAT(I3,F5.1,F6.2)
   DO 41 I=1,NPTS
41 READ INPUT TAPE 5,42,AFOF2(I), AHT(I),DIST(I)
42 FORMAT(F8.2,F7.2,F9.2)
   WRITE OUTPUT TAPE 11,43,NMPATH,ITYPE,PLENGT,TXLAT,TXLONM,RXBER,
   1SSN,SUNDEC,HOUR,NPTS,IFM
 3 FORMAT(10A6,I5/1X,F8.2,1X,F6.2,1X,F7.2,1X,F6.2/1X,F5.1,2X,F8.2,1X,
   1F5.2/1X,I9,I2)
   DO 44 I=1,NPTS
44 WRITE OUTPUT TAPE 11,42,AFOF2(I), AHT(I),DIST(I)
```

```
      READ INPUT TAPE 5,45,IES
   45 FORMAT(I3(
      IF(IES( 48,46,48
   46 WRITE OUTPUT TAPE 11,32,(ES,FREQL,FREQD,FREQH,ANGLL,ANGLD,ANGLH
 4601 WRITE OUTPUT TAPE 11,3201,NCHT
      IF(NCHT) 47,47,4602
 4602 DO 4603 I=1,NCHT
 4603 WRITE OUTPUT TAPE 11,3204,HFREQ(I)
   47 ISETS=ISETS+1
      IF(ISETS-NSETS) 39,39,2
   48 WRITE OUTPUT TAPE 11,45,IES
      READ INPUT TAPE 5,49,NPATCH
   49 FORMAT((4)
      READ INPUT TAPE 5,50,(PSTART(I),PEND(I),I=1,NPATCH)
   50 FORMAT(1X,2F9.2)
      WRITE OUTPUT TAPE 11,49,NPATCH
      WRITE OUTPUT TAPE 11,50,(PSTART(I),PEND(I(,I=1,NPATCH)
      OD 52 I=1,NPATCH
      READ INPUT TAPE 5,49,NPT
      READ INPUT TAPE 5,51,(ESD(ST((,J),TFDES((,J),J=1,NPT)
   51 FORMAT(1X,F8.2,1X,F5.2)
      WRITE OUTPUT TAPE 11,49,NPT
   52 WRITE OUTPUT TAPE 11,51,(ESD(ST((,J),TFOES((,J),J=1,NPT)
      WRITE OUTPUT TAPE 11,53,FRFQL,FRFQD,FREQH,ANGLL,ANGLD,ANGLH
   53 FORMAT(3F7.3/3F7.3)
      GO TO 4601
      END
```

```
C     STANFORD RAY TRACE PROGRAM
      FUNCTION FOE(SSN,COSX)
      IF(COSX-0.3420) 1,2,2
    1 FOE=0.0
      RETURN
    2 FOE=3.4*(1.0+0.0097*SSN)**0.25*(COSX**0.33)
      RETURN
      END
```

```
C     STANFORD RAY TRACE PROGRAM
      FUNCTION COSCH (PHIO,THETAO,T,PHI2,ALPHA,D)
      PI=3.1415927
      SINPHO=SINF(PHIO)
      COSPHO=COSF(PHIO)
      COSALP=COSF(ALPHA)
      SINPH1=SINPHO*COSF(D)+COSPHO*SINF(D)*COSALP
      COT=(SINPHO*COSALP-COSPHO*COSF(D)/SINF(D))/SINF(ALPHA)
      ATANG=ATANF(1.0/COT)
      IF(ALPHA-PI) 1,4,4
    1 IF(ATANG) 2,3,3
    2 THETA1=THETAO+ATANG
      GO TO 7
    3 THETA1=THETAO+(ATANG-PI)
      GO TO 7
    4 IF(ATANG) 6,6,5
    5 THETA1=THETAO+ATANG
      GO TO 7
    6 THETA1=THETAO+(PI+ATANG)
    7 THETA2=(T-12.0)*(3.1415927/12.0)
      COSCHI=SINPH1*SINF(PHI2)+COSF(ATANF(SINPHI/SQRTF(1.0-SINPH1**2)))*
     1COSF(PHI2)*COSF(THETA2-THETA1)
      RETURN
      END
```

```
C     STANFORD RAY TRACE PROGRAM
      SUBROUTINE POLY(X1,Y1,X2,Y2,X3,Y3,A,B,C)
      X1SQ=X1*X1
      X2SQ=X2*X2
      X3SQ=X3*X3
      D=X1SQ*(X2-X3)-X1*(X2SQ-X3SQ)+(X2SQ*X3-X3SQ*X2)
      D1=Y1*(X2-X3)-X1*(Y2-Y3)+(Y2*X3-Y3*X2)
      D2=X1SQ*(Y2-Y3)-Y1*(X2SQ-X3SQ)+(X2SQ*Y3-X3SQ*Y2)
      D3=X1SQ*(X2*Y3-X3*Y2)-X1*(X2SQ*Y3-X3SQ*Y2)+Y1*(X2SQ*X3-X3SQ*X2)
      A=D1/D
      B=D2/D
      C=D3/D
      RETURN
      END
```

```
C     STANFORD RAY TRACE PROGRAM
      SUBROUTINE UPREF
      COMMON REFIND,FREQ,FO,IREFL,H1,H2,HM,YM,COSI
      IF(FO) 2,1,2
    1 IREFL=3
      H2=HM+YM
      RETURN
    2 REFIND=(FREQ/FO)*COSI
      IF(REFIND-1.0) 3,4,5
    3 IREFL=1
      H2=HM-YM
      RETURN
    4 IREFL=4
      RETURN
    5 IF(REFIND-2.0) 7,7,6
    6 IREFL=3
      H2=HM+YM
      RETURN
    7 IREFL=2
      H2=HM-YM
      RETURN
      END
```

```
C     STANFORD RAY TRACE PROGRAM
      SUBROUTINE DWREF
      COMMON REFIND,FREQ,FO,IREFL,H1,H2,HM,YM,COSI
      IF(FO) 2,1,2
    1 IREFL=3
      H1=HM-YM
      RETURN
    2 REFIND=(FREQ/FO)*COSI
      IF(REFIND-1.0) 3,4,5
    3 IREFL=1
      H1=HM+YM
      RETURN
    4 IREFL=4
      RETURN
    5 IF(REFIND-2.0) 7,7,6
    6 IREFL=3
      H1=HM-YM
      RETURN
    7 IREFL=2
      H1=HM+YM
      RETURN
      END
```

```
C     STANFORD RAY TRACE PROGRAM
      SUBROUTINE PATH
      COMMON REFIND,FREQ,FO,IREFL,H1,H2,HM,YM,COSI,PDIST,GDIST,SHM,IRCNT
     1,FMODE,HTCALC,KK,FIDT,FIHT,RMODE,FNAME,ANGH1,ANGH2,LAYR,FLAYR,R,
     2COSBR,ANGLEI,P1000
      DIMENSION FIDT(100),FIHT(100),RMODE(10),FNAME(7)
      ARG1=COSBR/(R+H1)
      ARG2=COSBR/(R+H2)
      ANGH1=ATANF(ARG1/SQRTF(1.0-ARG1*ARG1))
      ANGH2=ATANF(ARG2/SQRTF(1.0-ARG2*ARG2))
      IREFL=IREFL
      GO TO (1,2,3),IREFL
    1 IRCNT=IRCNT+1
      IF(IRCNT-10) 12,12,11
   11 GDIST=P1000+500.0
      RETURN
   12 FMODE=10.0*FMODE+FLAYR
      DP1=(FREQ/FO)*YM*LOGF((1.0+REFIND)/(1.0-REFIND))
      DD1=(R/(R+SHM))*SINF(ANGLEI)*DP1
      DP2=(R+H2)*SINF(ANGH1-ANGH2)/SINF(ANGH1)
      DD2=R*(ANGH1-ANGH2)
      PDIST=PDIST+(DP1+DP2)
      GDIST=GDIST+(DD1+DD2)
      IF(HTCALC) 13,14,13
   13 IF(DD2) 15,16,16
   15 KK=KK-1
   16 KK=KK+1
      FIDT(KK)=GDIST-DD1/2.0
      FIHT(KK)=H2+YM*(1.0-SQRTF(1.0-REFIND*REFIND))
      IF(LAYR-4) 18,18,17
   17 FIHT(KK)=H1+2.0*YM-YM*(1.0-SQRTF(1.0-REFIND*REFIND))
   18 RMODE(IRCNT)=FNAME(LAYR)
   14 RETURN
    2 DP1=(FREQ/FO)*YM*LOGF((REFIND+1.0)/(REFIND-1.0))
      DD1=(R/(R+HM))*SINF(ANGLEI)*DP1
      DP2=(R+H2)*SINF(ANGH1-ANGH2)/SINF(ANGH1)
      DD2=R*(ANGH1-ANGH2)
      PDIST=PDIST+(DP1+DP2)
      GDIST=GDIST+(DD1+DD2)
      IF(HTCALC) 21,22,21
   21 KK=KK+1
      FIDT(KK)=GDIST
      FIHT(KK)=H2+2.0*YM
      IF(LAYR-4) 22,22,29
   29 FIHT(KK)=H1-2.0*YM
   22 RETURN
    3 DP1=(R+H2)*SINF(ANGH1-ANGH2)/SINF(ANGH1)
      DD1=R*(ANGH1-ANGH2)
      PDIST=PDIST+DP1
      GDIST=GDIST+DD1
      IF(HTCALC) 31,32,31
   31 KK=KK+1
      FIDT(KK)=GDIST
      FIHT(KK)=H2
      IF(LAYR-4) 32,32,33
   33 FIHT(KK)=H1
   32 RETURN
      END
```

```
C     STANFORD RAY TRACE PROGRAM
      SUBROUTINE CALCFO(TDIST,A,FO)
      DIMENSION A(250)
      INDEX=XINTF(TDIST/100.0)+1
      FO1=A(INDEX)
      FO2=A(INDEX+1)
      FINDEX=INDEX
      FO=FO1+((TDIST-100.0*(FINDEX-1.0))/100.0)*(FO2-FO1)
      RETURN
      END
```

```
C     STANFORD RAY TRACE PROGRAM
      DEGRADF(X)=(3.1415927/180.0)*X
      RADDEGF(X)=(180.0/3.1415927)*X
      FOF1F(X)=1.4*X
      ARCSINF(X)=ATANF(X/SQRTF(1.0-X*X))
      HTFUNF(X)=(2210.59/X**1.70831)*(9.44*(4.09-X)*(X-2.15)+46.0*(3.0-X
     1)*(4.09-X)*(X-2.15))
      PI=3.1415927
COMMENT INPUT FOR IONOSPHERIC GENERATORS
      COMMON REFINO,FREQ,FO,IREFL,H1,H2,HM,YM,COST,PDIST,GDIST,SHM,IRCNT
     1,FMODE,HTCALC,KK,FIDT,FIHT,RMODE,FNAME,ANGH1,ANGH2,LAYR,FLAYR,R,
     2COSRR,ANGLE1,PI000
      DIMENSION FIDT(100),FIHT(100),RMODE(10),FNAME(7),FHNAME(10)
      DIMENSION TFOF(200),TFOF1(200),TFOF2(200),THT(200)
      DIMENSION ROIST(50),FOF2(50),HT(50),FMU(50),FXF2(50)
      DIMENSION PSTART(20),PEND(20),ES0(5,20,10),TFOES(20,10)
      DIMENSION AGDIST(200),ABETA(200),AMODE(200)
      DIMENSION OLYTM(200),TFREQ(200),FREQNM(32)
      DIMENSION HOLDM(150,10),HOLDH(150),HOLDB(150),HOLDG(150)
      DIMENSION HOLDT(150),HCLOD(150),HOLDA(150),HFREQ(50)
      REWIND 11
      R=6367.0
    1 READ INPUT TAPE11,2,FHNAME,ITYPE
    2 FORMAT(10A6,I5)
      JK=0
      KL=0
      IPEN=0
      DO 5 I=1,200
      TFOF(I)=0.0
      TFOF1(I)=0.0
      TFOF2(I)=0.0
    5 THT(I)=0.0
```

```
      DO 6 I=1,90
      FOF2(I)=0.0
      HT(I)=0.0
    6 FMU(I)=0.0
      IF(ITYPE-1) 208,201,211
  201 READ INPUT TAPE11,202,PLENGT,FLAT,FLON,BER
  202 FORMAT(1X,F8.2,1X,F6.2,1X,F7.2,1X,F6.2)
      READ INPUT TAPE11,203,SSN,DECSUN,T
  203 FORMAT(1X,F5.1,2X,F6.2,1X,F5.2)
      READ INPUT TAPE11,204,N
  204 FORMAT(1X,I3)
      READ INPUT TAPE11,205,(RDIST(I),I=1,N)
  205 FORMAT(1X,F8.2)
      IF(NOPT) 206,209,206
      GO TO 209
  208 READ INPUT TAPE11,203,SSN,DECSUN,T
  209 READ INPUT TAPE11,210,(FXF2(I),FMU(I),I=1,N)
  210 FORMAT(1X,F5.2,1X,F6.2)
      GO TO 215
  211 READ INPUT TAPE11,202,PLENGT,FLAT,FLON,BER
      READ INPUT TAPE11,203,SSN,DECSUN,T
      READ INPUT TAPE11,204,N
  213 READ INPUT TAPE11,214,(RDIST(I),FXF2(I),HT(I),I=1,N)
  214 FORMAT(1X,F8.2,1X,F5.2,1X,F6.2)
  215 FLATR=DEGRADF(FLAT)
      FLONR=DEGRADF(FLON)
      BERR=DEGRADF(BER)
      DECR=DEGRADF(DECSUN)
      PFAV=1.0
      DO 901 I=1,N
  901 FOF2(I)=FXF2(I)
      IF (ITYPE-1) 9013,9013,1001
 9013 DO 10 I=1,N
   10 HT(I)=HTFUNF(FMU(I)/(FOF2(I)))
COMMENT GENERATE E LAYER
 1001 HME=120.0
      YME=20.0
      D=0.0
      I=1
      SUMCOS=0.0
   11 IF(D-PLENGT) 12,12,13
   12 COSX=COSCH (FLATR,FLONR,T,DECR,BERR,D/R)
      TFOE(I)=FOE(SSN,COSX)
      D=D+100.0
      I=I+1
      IF(COSX) 1201,1202,1202
 1201 COSX=0.0
 1202 SUMCOS=SUMCOS+COSX
      GO TO 11
   13 NE=I-1
      AVCOS=SUMCOS/FLOATF(NE)
      IF(AVCOS) 1299,1299,1300
 1299 COSCHI=0.0
      GO TO 1301
 1300 COSCHI=COSF(0.881*ARCSINF(SQRTF(1.0-AVCOS**2)))**1.3
 1301 DI=(1.0+0.0037*SSN)*COSCHI
COMMENT GENERATE F1 LAYER
      HMF1=210.0
      YMF1=60.0
      DO 14 I=1,NE
   14 TFOF1(I)=FOF1F(TFOE(I))
COMMENT GENERATE F2 LAYER
      J=1
      D=0
```

```
      K=1
      LIM=(N+1)/2
      DO 18 I=1,LIM
      J1=J+1
      J2=J+2
      RDJ=RDIST(J)/PLENGT
      RDJ1=RDIST(J1)/PLENGT
      RDJ2=RDIST(J2)/PLENGT
      CALL POLY(RDJ,FOF2(J),RDJ1,FOF2(J1),RDJ2,FOF2(J2),A1,B1,C1)
      CALL POLY(RDJ,HT(J),RDJ1,HT(J1),RDJ2,HT(J2),A2,B2,C2)
 1501 IF((D/PLENGT)-RDJ2) 16,16,17
   16 X=D/PLENGT
      TFOF2(K)=((A1*X+B1)*X)+C1
      THT(K)=((A2*X+B2)*X)+C2
      D=D+100.0
      K=K+1
      GO TO 1501
   17 J=J2
   18 CONTINUE
      DO 19 I=K,200
      TFOE(I)=TFOE(K-1)
      TFOF1(I)=TFOF1(K-1)
      TFOF2(I)=TFOF2(K-1)
   19 THT(I)=THT(K-1)
      WRITE OUTPUT TAPE 6,20,FMNAME
   20 FORMAT(1H1,23HIONOSPHERIC PROFILE FOR,10A6)
      WRITE OUTPUT TAPE 6,21
   21 FORMAT(1H0,1X,34HFOE   FOF1   FOF2   HT FOF2     RANGE)
      D=0.0
      DO 2201 J=1,K
      WRITE OUTPUT TAPE 6,22,TFOE(J),TFOF1(J),TFOF2(J),THT(J),D
   22 FORMAT(1H0,F4.1,2X,F4.1,2X,F4.1,9X,F6.2,3X,F8.2)
 2201 D=D+100.0
COMMENT GENERATE ES LAYERS,IF ANY
      READ INPUT TAPE11,23,IES
   23 FORMAT(1X,I2)
      IF(IES) 24,31,24
   24 DO 25 I=1,20
      PSTART(I)=0.0
   25 PEND(I)=0.0
      DO 26 I=1,20
      DO 26 J=1,10
      ESDIST(I,J)=0.0
   26 TFOES(I,J)=0.0
      READ INPUT TAPE11,27,NPATCH
   27 FORMAT(1X,I3)
      READ INPUT TAPE11,28,(PSTART(I),PEND(I),I=1,NPATCH)
   28 FORMAT(1X,2F9.2)
      WRITE OUTPUT TAPE 6,2801
 2801 FORMAT(1H0,18HES PATCHES PRESENT/1H0,33HPATCH STARTS AT      PATCH
     1ENDS AT)
      WRITE OUTPUT TAPE 6,2802,(PSTART(I),PEND(I),I=1,NPATCH)
 2802 FORMAT(1H0,4X,F8.2,12X,F8.2)
      DO 3001 I=1,NPATCH
      READ INPUT TAPE11,29,NPTS
   29 FORMAT(1X,I3)
      READ INPUT TAPE11,30,(ESDIST(I,J),TFOES(I,J),J=1,NPTS)
   30 FORMAT(1X,F8.2,1X,F5.2)
 3001 CONTINUE
   31 NMES=100.0
COMMENT ALPHA-NUMERIC EQUIVALENTS OF MODE REFLECTION NAMES
      FNAME(1)=3H,ES
      FNAME(2)=3H,E
      FNAME(3)=3H,F1
```

```
      FNAME(4)=3H F2
      FNAME(5)=3H F1
      FNAME(6)=3H E
      FNAME(7)=3H ES
      P1000=PLENGT+1000.0
COMMENT READ FREQUENCY RANGE TO BE USED
      READ INPUT TAPE11,32,FREQL,FREQD,FREQM
   32 FORMAT(3F9.3)
COMMENT READ TAKE-OFF ANGLE RANGE TO BE USED
      READ INPUT TAPE11,33,BETAL,BETAD,BETAM
   33 FORMAT(3F7.3)
COMMENT START RAY TRACING PORTION OF PROGRAM
      READ INPUT TAPE 11,3301,NCHT
 3301 FORMAT(I4)
      IF(NCHT) 3304,3304,3302
 3302 DO 331 I=1,NCHT
  331 READ INPUT TAPE 11,3303,HFREQ(I)
 3303 FORMAT(F7.3)
 3304 FREQ=FREQL
   34 IF(FREQ-FREQM) 35,35,11501
   35 HTC C=0
      HTCAL=0
      INTERP=1
      LL=0
      IF(IPEN) 11501,36,11501
   36 IPEN=1
      BETA=BETAL
   37 IF(BETA-BETAM) 38,38,9401
COMMENT CALCULATE CONSTANTS FOR A GIVEN BETA
   38 BETAR=DEGRADF(BETA)
      COSBR=COSF(BETAR)*R
      DANGLE=3.1415927-(BETAR+1.5707963)
      ANGES=ARCSINF(COSBR/(HMES+R))
      COSES=COSF(ANGES)
      RANGES=R*(DANGLE-ANGES)
      ANGE=ARCSINF(COSBR/(HME+R))
      COSE=COSF(ANGE)
      RANGE=R*(DANGLE-ANGE)
      ANGF1=ARCSINF(COSBR/(HMF1+R))
      COSF1=COSF(ANGF1)
      RANGF1=R*(ANGF-ANGF1)
      SECANG=1.0/SQRTF(1.0-(COSPR/(R+79.0))**2)
      GDIST=0.0
      PDIST=0.0
      IRCNT=0
      FMODE=0.0
      KK=0
COMMENT UP-GOING ES LAYER
 9801 IF(ITES) 39,53,39
   39 I=0
      TDIST=GDIST+RANGES
   40 I=I+1
      IF(I-NPATCH) 41,41,68
   41 IF(TDIST-PSTART(I)) 68,68,42
   42 IF(TDIST-PEND(I)) 43,40,40
   43 J=1
   44 IF(TDIST-ESDIST(I,J)) 46,46,45
   45 J=J+1
      GO TO 44
   46 FO1=TFOES(I,J-1)
      FO2=TFOES(I,J)
      D1=ESDIST(I,J-1)
      D2=ESDIST(I,J)
      FO=FO1+((TDIST-D1)/(D2-D1))*(FO2-FO1)
```

```
      IF(FO) 47,68,47
   47 REFIND=(FREQ/FO)*COSES
      IF(REFIND-1.0) 48,68,68
   48 IRCNT=IRCNT+1
      IF(IRCNT-10) 49,49,93
   49 LAYR=1
      FLAYR=1.0
      FMODE=FMODE*10.0+FLAYR
      DR1=(R+HMES)*SINF(DANGLE-ANGES)/SINF(DANGLE)
      DD1=R*(DANGLE-ANGES)
      PDIST=PDIST+DRI
      GDIST=GDIST+DD1
      IF(GDIST-P1000) 50,50,93
   50 IF(HTCALC) 51,52,51
   51 KK=KK+1
      FIDT(KK)=GDIST
      FIHT(KK)=HMES
      RMODE(IRCNT)=FNAME(LAYR)
   52 IFRMES=0
      GO TO 89
   53 IFRMES=0
      GO TO 68
COMMENT DOWN-GOING FS LAYER
   54 IF(IES) 55,67,55
   55 I=0
      TDIST=GDIST+R*(ANGES-ANGH1)
 5501 I=I+1
      IF(I-NPATCH) 56,56,89
   56 IF(TDIST-PSTART(I)) 89,89,57
   57 IF(TDIST-PEND(I)) 58,5501,5501
   58 J=1
   59 IF(TDIST-ESDIST(I,J)) 61,61,60
   60 J=J+1
      GO TO 59
   61 FO1=TFDES(I,J-1)
      FO2=TFDES(I,J)
      D1=ESDIST(I,J-1)
      D2=ESDIST(I,J)
      FO=FO1+((TDIST-D1)/(D2-D1))*(FO2-FO1)
      IF(FO) 62,89,62
   62 REFIND=(FREQ/FO)*COSES
      IF(REFIND-1.0) 63,89,89
   63 IRCNT=IRCNT+1
      IF(IRCNT-10) 6301,6301,93
 6301 LAYR=7
      FLAYR=7.0
      FMODE=FMODE*10.0+FLAYR
      IFRMES=1
      DR1=(R+H1)*SINF(ANGES-ANGH1)/SIN(ANGES)
      DD1=R*(ANGES-ANGH1)
      PDIST=PDIST+DPI
      GDIST=GDIST+DD1
      IF(GDIST-P1000) 64,64,93
   64 IF(HTCALC) 65,66,65
   65 KK=KK+1
      FIDT(KK)=GDIST
      FIHT(KK)=HMES
      RMODE(IRCNT)=FNAME(LAYR)
   66 GO TO 74
   67 GO TO 89
COMMENT UP-GOING E LAYER
   68 HM=HME
      YM=YME
      SHM=HM
```

```
      ANGLEI=ANGE
      COSI=COSE
      HI=0.0
      LAYR=2
      FLAYR=2.0
      CALL CALCFO(GDIST+RANGE,TFOE,FO)
      IFRMES=0
      CALL UPREF
      IF(IREFL-4) 69,93,69
   69 CALL PATH
      IREFL=IREFL
      IF(GDIST-P1000) 70,70,93
   70 GO TO (89,74,74),IREFL
COMMENT DOWN-GOING F LAYER
   71 HM=HME
      YM=YME
      SHM=-HM
      ANGLEI=ANGE
      COSI=COSE
      H2=HMF1-YMF1
      LAYR=6
      FLAYR=6.0
      CALL CALCFO(GDIST+RANGF1,TFOE,FO)
      IFRMES=0
      CALL DWREF
      IF(IREFL-4) 72,93,72
   72 CALL PATH
      IREFL=IREFL
      IF(GDIST-P1000) 73,73,93
   73 GO TO (74,54,54),IREFL
COMMENT UP-GOING F1 LAYER
   74 HM=HMF1
      YM=YMF1
      SHM=HM
      ANGLEI=ANGF1
      COSI=COSF1
      HI=HMF+YME
      IF(IFRMES) 75,76,75
   75 HI=HMES
   76 LAYR=3
      FLAYR=3.0
      CALL CALCFO(GDIST+RANGF1,TFOF1,FO)
      CALL UPREF
      IF(IREFL-4) 77,93,77
   77 CALL PATH
      IREFL=IREFL
      IF(GDIST-P1000) 78,78,93
   78 GO TO (71,82,82),IREFL
COMMENT DOWN-GOING F1 LAYER
   79 HM=HMF1
      YM=YMF1
      SHM=-HM
      ANGLEI=ANGF1
      COSI=COSF1
      H2=HMF2-YMF2
      LAYR=5
      FLAYR=5.0
      TDIST=GDIST+R*(ANGF1-ARCSINF(COSBR/(H2+R)))
      CALL CALCFO(TDIST,TFOF1,FO)
      CALL DWREF
      IF(IREFL-4) 80,93,80
   80 CALL PATH
      IREFL=IREFL
      IF(GDIST-P1000) 81,81,93
```

```
81 GO TO (82,71,71),IREFL
COMMENT F2 LAYER
82 HMF2=0.0
   THMF2=100.0
   TOIST=GOIST
   TRANGE=0.0
   ICNT=0
   ANGH1=ARCSINF(COSBR/(R+(HMF1+YMF1)))
83 IF(ABSF(THMF2-HMF2)-10.0) 86,86,84
84 IF(ICNT-20) 85,85,93
85 HMF2=THMF2
   CALL CALCFO(TDIST,THT,THMF2)
   ANGH2=ARCSINF(COSBR/(R+THMF2))
   TOIST=TDIST-TRANGE
   TRANGE=R*(ANGH1-ANGH2)
   TDIST=TDIST+TRANGE
   ICNT=ICNT+1
   GO TO 83
86 HMF2=THMF2
   ANGF2=ARCSINF(COSBR/(R+HMF2))
   COSF2=COSF(ANGF2)
   YMF2=(0.4/1.4)*HMF2
   HM=HMF2
   SHM=HM
   YM=YMF2
   ANGLEI=ANGF2
   H1=HMF1+YMF1
   LAYR=4
   FLAYR=4.0
   CALL CALCFO(TOIST,TFOF2,FO)
   REFINO=(FREQ/FO)*COSF2
   IF(REFIND-1.0) 87,93,93
87 IREFL=1
   H2=HMF2-YMF2
   CALL PATH
   REFL=IREFL
   IF(GOIST-P1000) 88,88,93
88 GO TO (79,93,93),IREFL
COMMENT TRACE RAY TO GROUND
89 H1=0.0
   H2=HMF-YMF
   IREFL=3
   LAYR=8
   CALL PATH
   INTERP=INTERP
   IF(RDIST-P1000) 90,90,93
90 IF(RDIST-(PLENGT-1000.0)) 3801,91,91
91 GO TO (92,100),INTERP
92 IPEN=0
   LL=LL+1
   AGDIST(LL)=GDIST
   ABETA(LL)=BETA
   AMODE(LL)=FMODE
   GO TO 3801
93 GO TO (94,100),INTERP
94 BETA=BETA+BETAD
   GO TO 97
9401 DO 95 I=1,10
95 RMODE(I)=6060606060
   II=1
   HTCALC=1
   IF(NCHT) 952,951,952
951 HTCAL=0
   GO TO 9501
```

```
  952 DO 953 I=1,NCHT
      IF(FREQ-HFREQ(I)) 953,954,953
  953 CONTINUE
      HTCAL=0
      GO TO 9501
  954 HTCAL=1
 9501 IF(II-(LL-1)) 9502,9502,9901
 9502 IF(AMODE(II)-AMODE(II+1)) 99,96,99
   96 IF(AGDIST(II)-PLENGT) 99,97,97
   97 IF(AGDIST(II+1)-PLENGT) 98,98,99
   98 BETA=ABETA(II)+((PLENGT-AGDIST(II))/(AGDIST(II+1)-AGDIST(II)))*
     1(ABETA(II+1)-ABETA(II))
      INTERP=2
      GO TO 38
   99 II=II+1
      GO TO 9501
 9901 FREQ=FREQ+FREQD
      GO TO 34
  100 IF(GDIST-(PLENGT+100.0)) 101,101,99
  101 IF(GDIST-(PLENGT-100.0)) 3801,102,102
  102 IF(FMODE-AMODE(II)) 99,103,99
  104 FORMAT(1H1,10A6)
  103 DB=615.5*DI*FLOATF(IRCNT)*SECANG/(FREQ*PFA\)**1.98
  105 FORMAT(1H0,11HPATH LENGTH,F9.2,3H KM,5X,7HTX LAT ,F7.2,4H DEG,5X,
     18HTX LONG ,F7.2,4H DEG,5X,11HRX BEARING ,F7.2,4H DEG)
      JK=JK+1
      TIME=(PDIST+(GDIST-PLENGT))/300.0
      KL=KL+1
      DO 10702 I=1,10
10702 HOLDM(KL,I)=RMODE(I)
      HOLDH(KL)=FREQ
      HOLDA(KL)=BETA
      HOLDG(KL)=GDIST
      HOLDT(KL)=TIME
      HOLDD(KL)=GDIST-PLENGT
      HOLDB(KL)=DB
      FLONO=-FLON
      IF(HTCAL) 108,1085,108
  108 WRITE OUTPUT TAPE 6,104,FHNAME
      WRITE OUTPUT TAPE 6,105,PLENGT,FLAT,FLONO,BER
      WRITE OUTPUT TAPE 6,1081,(RMODE(I),I=1,10),FREQ,BETA
 1081 FORMAT(1H0,5HMODE ,10AL/1H0,F7.3,1X,2HMC,5X,F7.3,1X,7HDEGREES)
      WRITE OUTPUT TAPE 6,1082
 1082 FORMAT(1H0,2X,6HHEIGHT,3X,5HRANGE)
      DO 1083 IJ=1,KK
 1083 WRITE OUTPUT TAPE 6,1084,FIHT(IJ),FIDT(IJ)
 1084 FORMAT(1H0,F8.2,F10.2)
 1085 DO 111 I=1,10
B 111 RMODE(I)=606060606060
      GO TO 99
  112 WRITE OUTPUT TAPE 6,113
  113 FORMAT(1H0,14HRAY PENETRATES)
 1121 WRITE OUTPUT TAPE 6,104,FHNAME
      FLONO=-FLON
      WRITE OUTPUT TAPE 6,105,PLENGT,FLAT,FLONO,BER
      WRITE OUTPUT TAPE 6,116
  116 FORMAT(1H0, 99H                                  MODE
     1              FREQ  BETA  DIST       TIME   DIFF      DB)
      DO 117 LK=1,KL
  117 WRITE OUTPUT TAPE 6,118,(HOLDM(LK,I),I=1,10),HOLDH(LK),HOLDA(LK),
     1HOLDG(LK),HOLDT(LK),HOLDD(LK),HOLDB(LK)
  118 FORMAT(1H0,10A6,F6.2,F6.2,F9.2,F6.2,F8.2,F7.2)
      GO TO 1
      END
```

IONOSPHERIC PROFILE FOR 6 OCTOBER 1962 1737.36 GMT PAHOA/BEDFORD PATH

FOE	FOF1	FOF2	HT FOF2	RANGE
3.3	4.6	7.5	205.55	0.
0.	0.	7.5	207.13	100.00
0.	0.	7.5	208.93	200.00
0.	0.	7.5	210.97	300.00
0.	0.	7.5	213.23	400.00
0.	0.	7.6	215.73	500.00
0.	0.	7.6	218.45	600.00
0.	0.	7.6	221.39	700.00
0.	0.	7.6	224.57	800.00
0.	0.	7.6	229.28	900.00
2.5	3.6	7.6	233.33	1000.00
2.6	3.6	7.6	236.64	1100.00
2.6	3.6	7.6	239.19	1200.00
2.6	3.7	7.6	241.01	1300.00
2.6	3.7	7.6	242.07	1400.00
2.6	3.7	7.6	242.39	1500.00
2.7	3.7	7.6	241.97	1600.00
2.7	3.8	7.6	242.79	1700.00
2.7	3.8	7.6	243.30	1800.00
2.7	3.8	7.6	243.33	1900.00
2.7	3.8	7.6	242.87	2000.00
2.8	3.9	7.6	241.93	2100.00
2.8	3.9	7.6	240.50	2200.00
2.8	3.9	7.6	238.58	2300.00
2.8	3.9	7.6	236.18	2400.00
2.8	3.9	7.6	235.12	2500.00
2.8	4.0	7.6	234.25	2600.00
2.8	4.0	7.6	233.34	2700.00
2.9	4.0	7.6	232.37	2800.00
2.9	4.0	7.5	231.35	2900.00
2.9	4.0	7.5	230.27	3000.00
2.9	4.1	7.5	229.14	3100.00
2.9	4.1	7.5	227.96	3200.00
2.9	4.1	7.5	224.88	3300.00
2.9	4.1	7.5	222.06	3400.00
2.9	4.1	7.5	219.99	3500.00
3.0	4.1	7.5	218.67	3600.00
3.0	4.2	7.5	218.09	3700.00
3.0	4.2	7.5	218.27	3800.00
3.0	4.2	7.5	219.20	3900.00
3.0	4.2	7.5	220.97	4000.00
3.0	4.2	7.5	222.05	4100.00
3.0	4.2	7.5	222.96	4200.00
3.0	4.2	7.5	223.90	4300.00
3.0	4.2	7.5	224.86	4400.00
3.0	4.3	7.5	225.85	4500.00
3.0	4.3	7.6	226.85	4600.00
3.1	4.3	7.6	227.88	4700.00
3.1	4.3	7.6	228.93	4800.00
3.1	4.3	7.6	230.01	4900.00
3.1	4.3	7.7	232.97	5000.00
3.1	4.3	7.7	235.12	5100.00
3.1	4.3	7.7	237.25	5200.00
3.1	4.3	7.7	239.36	5300.00
3.1	4.3	7.7	241.45	5400.00
3.1	4.3	7.7	243.52	5500.00
3.1	4.4	7.7	245.58	5600.00
3.1	4.4	7.7	247.87	5700.00
3.1	4.4	7.7	250.19	5800.00
3.1	4.4	7.7	252.39	5900.00
3.1	4.4	7.7	254.49	6000.00
3.1	4.4	7.8	256.48	6100.00
3.1	4.4	7.8	258.36	6200.00
3.1	4.4	7.8	260.13	6300.00
3.1	4.4	7.8	261.79	6400.00
3.1	4.4	7.8	264.08	6500.00
3.1	4.4	7.8	266.26	6600.00
3.1	4.4	7.8	267.80	6700.00
3.2	4.4	7.9	268.70	6800.00
3.2	4.4	7.9	268.96	6900.00
3.2	4.4	7.9	268.57	7000.00
3.2	4.4	7.9	267.55	7100.00
3.2	4.4	7.9	265.89	7200.00
3.2	4.4	7.9	263.96	7300.00
3.2	4.4	8.0	262.29	7400.00
3.2	4.4	8.0	260.78	7500.00
3.2	4.4	8.0	259.41	7600.00
3.2	4.4	8.0	258.20	7700.00
3.2	4.4	8.0	257.15	7800.00
3.2	4.4	8.1	256.25	7900.00
3.2	4.4	8.1	255.50	8000.00
3.2	4.4	8.1	255.50	8100.00

6 OCTOBER 1962 1737.36 GMT PAHOA/BEDFORD PATH

PATH LENGTH 8045.35 KM   TX LAT 19.50 DEG   TX LONG -154.95 DEG   RX BEARING 50.26 DEG

				MODE						FREQ	BETA	DIST	TIME	DIFF	DB
.E	.E	.E	.E							4.00	1.18	8039.09	27.10	-6.26	649.57
.F2	.E	.E	.E	.E	.E	.E	.E	.E	.E	4.00	13.19	8041.41	27.98	-3.94	894.86
.E	.E	.E	.E							5.00	1.22	8037.90	27.09	-7.45	417.28
.E	.E	.E	.E							6.00	1.28	8036.66	27.09	-8.69	290.56
.E	.E	.E	.E							7.00	1.35	8035.48	27.09	-9.87	213.86
.F2	.E	.E	.E	.E	.E	.E	.E	.E		7.00	12.50	8026.50	27.84	-18.85	275.91
.E	.E	.E	.E							8.00	1.44	6034.57	27.09	-10.78	163.91
.E	.E	.E	.E							9.00	1.54	8034.34	27.10	-11.01	129.54
.E	.E	.E	.E							10.00	1.68	8035.43	27.12	-9.92	104.55
.F2	.F2	.F2	.F2	.F2	.F2	.F2				10.00	23.19	8015.76	30.17	-29.59	66.07
.E	.E	.E	.E							11.00	1.85	8039.26	27.16	-6.09	86.48
.F2	.F1	.F1	.F1	.F1						11.00	13.20	7989.22	28.10	-56.13	60.34
.F2	.F2	.F2	.F2	.F2	.F2	.F2				11.00	21.70	8024.18	29.87	-21.17	57.77
.F2	.F2	.F2	.F2	.F2	.F2	.F2	.F2			11.00	24.17	8041.84	30.53	-3.51	60.41
.F1	.E	.E	.F	.E						12.00	7.01	8043.03	27.63	-2.32	71.98
.F2	.F2	.F2	.F2	.F2	.F2					12.00	18.43	8021.89	29.23	-23.46	47.56
.F2	.F2	.F2	.F2	.F2	.F2	.F2				12.00	20.90	8040.18	29.80	-5.17	50.14
.F2	.F2	.F2	.F2	.F2	.F2	.F2	.F2			12.00	23.91	8042.95	30.48	-2.40	51.30
.F2	.F2	.F2	.F2	.F2						13.00	15.03	8042.09	28.85	-3.26	39.52
.F2	.F2	.F2	.F2	.F2	.F2					13.00	17.66	8031.97	29.15	-13.38	41.76
.F2	.F2	.F2	.F2	.F2	.F2	.F2				13.00	20.65	8042.70	29.77	-2.65	43.22
.F2	.F2	.F2	.F2	.F2	.F2	.F2	.F2			13.00	24.35	8037.02	30.58	-8.33	43.13
.F2	.F2	.F2	.F2	.F2						14.00	14.17	8038.79	28.68	-6.56	35.63
.F2	.F2	.F2	.F2	.F2	.F2					14.00	17.32	8037.78	29.13	-7.57	36.79
.F2	.F2	.F2	.F2	.F2	.F2	.F2				14.00	20.86	8048.51	29.87	3.16	37.01
.F2	.F2	.F2	.F2							15.00	10.72	8018.50	28.16	-26.85	29.89
.F2	.F2	.F2	.F2	.F2						15.00	13.72	8033.63	28.57	-11.72	31.79
.F2	.F2	.F2	.F2	.F2	.F2					15.00	17.35	8042.26	29.18	-3.09	32.05
.F2	.F2	.F2	.F2	.F2	.F2	.F2				15.00	22.10	8045.07	30.17	-0.28	30.80
.F2	.F2	.F2	.F2							16.00	10.03	8044.89	28.24	-0.46	27.36
.F2	.F2	.F2	.F2	.F2						16.00	13.52	8036.26	28.56	-9.09	28.27
.F2	.F2	.F2	.F2	.F2	.F2					16.00	17.82	8047.48	29.33	2.13	27.63
.F2	.F2	.F2								17.00	6.29	8026.02	27.85	-19.33	22.57
.F2	.F2	.F2	.F2							17.00	9.66	8040.63	28.17	-4.72	24.79
.F2	.F2	.F2	.F2	.F2						17.00	13.56	8043.77	28.63	-1.58	25.01
.F2	.F2									18.00	0.26	8055.64	27.74	10.29	16.68
.F2	.F2	.F2								18.00	5.64	8046.42	27.92	1.07	20.88
.F2	.F2	.F2	.F2							18.00	9.49	8042.59	28.17	-2.76	22.35
.F2	.F2	.F2	.F2	.F2						18.00	13.91	8040.59	28.69	-4.76	21.95
.F2	.F2	.F2								19.00	5.28	8040.53	27.84	-4.82	19.12
.F2	.F2	.F2	.F2							19.00	9.51	8042.76	28.18	-2.59	20.05
.F2	.F2	.F2	.F2	.F2						19.00	15.25	8033.20	28.90	-12.15	18.44
.F2	.F2	.F2								20.00	5.08	8042.24	27.84	-3.11	17.45
.F2	.F2	.F2	.F2							20.00	9.73	8042.64	28.22	-2.71	17.89
.F2	.F2	.F2								21.00	5.02	8044.62	27.86	-0.73	15.90
.F2	.F2	.F2	.F2							21.00	10.22	8045.00	28.32	-0.35	15.80
.F2	.F2	.F2								22.00	[illegible].09	8042.56	27.86	-2.79	14.45
.F2	.F2	.F2								23.00	5.29	6037.81	27.86	-7.54	13.09
.F2	.F2	.F2								24.00	5.66	8040.43	27.93	-4.92	11.79
.F2	.F2	.F2								25.00	6.71	8016.11	27.91	-29.24	10.27

6 OCTOBER 1962 1737.36 GMT PAHOA/BEOFORO PATH

PATH LENGTH 8045.35 KM TX LAT 19.50 OEG TX LONG -154.95 DEG RX BEARING 50.26 OEG

MOOE .F1 .E .E .E .E

12.000 MC 7.005 OEGREES

HEIGHT	RANGE
140.00	753.85
187.17	1095.09
100.00	1928.36
0.	2512.50
112.74	3228.64
0.	3944.77
110.83	4635.49
0.	5326.21
110.00	6006.97
0.	6687.74
109.73	7365.38
0.	8043.03

6 OCTOBER 1962 1737.36 GMT PAHOA/BEOFORO PATH TX LONG -154.95 OEG RX BEARING 50.26 OEG

PATH LENGTH 8045.35 KM TX LAT 19.50 OEG

MOOE .F2 .F2 .F2 .F2 .F2 .F2

12.000 MC 18.426 DEGREES

HEIGHT	RANGE
140.00	377.77
169.34	480.10
150.00	558.15
100.00	682.74
0.	960.20
140.00	1353.26
189.43	1599.69
150.00	1822.38
100.00	1964.47
0.	2241.93
140.00	2638.68
179.96	2893.49
150.00	3124.21
100.00	3269.73
0.	3547.19
140.00	3947.12
174.68	4222.29
150.00	4473.56
100.00	4621.89
0.	4899.35
140.00	5301.74
193.95	5655.36
150.00	5987.47
100.00	6137.81
0.	6415.27
140.00	6819.16
204.79	7218.02
150.00	7593.56
100.00	7744.43
0.	8021.89

6 OCTOBER 1962 1737.36 GMT PAHOA/BEDFORD PATH TX LONG -154.95 DEG RX BEARING 50.26 DEG

PATH LENGTH 8045.35 KM TX LAT 19.50 DEG

MODE .F2 .F2 .F2 .F2 .F2 .F2 .F2

12.000 MC 20.904 DEGREES

HEIGHT	RANGE
140.00	335.66
170.63	437.73
150.00	517.86
100.00	630.00
0.	875.45
140.00	1221.78
192.09	1437.13
150.00	1630.90
100.00	1755.06
0.	2000.51
140.00	2349.05
185.51	2566.21
150.00	2761.59
100.00	2887.79
0.	3133.23
140.00	3483.69
172.86	3687.70
150.00	3869.37
100.00	3997.23
0.	4242.68
140.00	4594.63
182.54	4833.54
150.00	5050.80
100.00	5179.98
0.	5425.43
140.00	5778.50
203.42	6074.58
150.00	6349.59
100.00	6479.62
0.	6725.06
140.00	7078.75
205.60	7382.56
150.00	7664.54
100.00	7794.74
0.	8040.18

6 OCTOBER 1962 1737.36 GMT PAHOA/BEDFORD PATH

PATH LENGTH 8045.35 KM TX LAT 19.50 DEG TX LONG -154.95 DEG RX BEARING 50.26 DEG

MODE .F2 .F2 .F2 .F2 .F2 .F2 .F2 .F2

12.000 MC 23.913 DEGREES

HEIGHT	RANGE
140.00	293.76
173.20	398.68
150.00	484.11
100.00	583.39
0.	797.36
140.00	1091.12
195.22	1284.51
150.00	1458.78
100.00	1566.10
0.	1780.07
140.00	2082.37
192.95	2280.54
150.00	2459.57
100.00	2568.11
0.	2782.07
140.00	3085.53
182.28	3270.43
150.00	3435.88
100.00	3545.43
0.	3759.39
140.00	4063.79
181.43	4253.98
150.00	4424.74
100.00	4535.11
0.	4749.08
140.00	5054.20
193.38	5272.78
150.00	5472.17
100.00	5583.17
0.	5797.13
140.00	6102.78
211.32	6361.74
150.00	6601.58
100.00	6712.95
0.	6926.92
140.00	7232.82
208.56	7484.94
150.00	7717.57
100.00	7828.99
0.	8042.95

6 OCTOBER 1962 1737.36 GMT PAHOA/BEOFORD PATH

PATH LENGTH 8045.35 KM   TX LAT 19.50 OEG   TX LONG -154.95 OEG   RX BEARING 50.26 OEG

MOOE .F2 .F2 .F2

17.000 MC   6.286 OEGREES

HEIGHT	RANGE
140.00	795.34
188.09	1164.93
150.00	1494.02
100.00	1755.57
0.	2376.09
140.00	3229.29
169.62	3636.69
150.00	4001.77
100.00	4285.17
0.	4905.69
140.00	5777.34
208.33	6457.01
150.00	7109.07
100.00	7405.51
0.	8026.02

6 OCTOBER 1962 1737.36 GMT PAHOA/BEOFORO PATH

PATH LENGTH 8045.35 KM   TX LAT 19.50 OEG   TX LONG -154.95 OEG   RX BEARING 50.26 OEG

MOOE .F2 .F2 .F2 .F2

17.000 MC   9.659 OEGREES

HEIGHT	RANGE
140.00	625.52
182.75	825.41
150.00	989.93
100.00	1199.92
0.	1674.83
140.00	2328.72
185.03	2663.34
150.00	2962.70
100.00	3181.45
0.	3656.36
140.00	4318.01
181.36	4680.38
150.00	5007.72
100.00	5232.91
0.	5707.82
140.00	6374.27
213.76	6873.11
150.00	7337.97
100.00	7565.72
0.	8040.63

6 OCTOBER 1962 1737.36 GMT PAHOA/BEDFORD PATH

PATH LENGTH 8045.35 KM   TX LAT 19.50 DEG   TX LONG -154.95 DEG   RX BEARING 50.26 DEG

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17.000 MC   13.565 DEGREES

HEIGHT	RANGE
140.00	490.10
181.88	678.10
150.00	836.21
100.00	1003.83
0.	1368.75
140.00	1873.05
197.43	2178.60
150.00	2455.21
100.00	2626.44
0.	2991.36
140.00	3498.91
178.86	3763.34
150.00	3997.72
100.00	4171.58
0.	4536.50
140.00	5046.28
198.22	5380.85
150.00	5686.20
100.00	5861.86
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